Twenty-First Century Snake Oil

Why the United States Should Reject Biofuels as Part of a Rational National Security Energy Strategy

Captain T. A. 'Ike' Kiefer

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Cover Photos

Background and back cover: Ruins of Chan Chan, capital city of the Chimu Empire. Photo courtesy of Håkan Svensson via Wikimedia Commons.

Foreground: Fritz Haber, winner of 1918 Nobel Prize for discovering how to make ammonia from natural gas. Photo in the public domain.

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Author's Biography

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Disclaimer

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Executive Summary

Biofuels are today's quintessential example of something that sounds good in theory but proves counterproductive in practice. The US Military has been funding biofuel research, buying test and demonstration quantities of biofuels, and is now funding construction of new bio-refineries with the stated objectives of helping to commercialize production, increase the domestic fuel supply, reduce dependence upon foreign oil, and reduce fuel costs associated with oil price fluctuations. The military's role is part of a larger federal government energy strategy pursued by consecutive Presidential Administrations to migrate the US economy away from fossil fuels toward domestically produced biomass-based fuels that are purported to be perpetually renewable, easier on the environment, and enhancing to national security. Current military and national energy policy and strategy need to be informed by a better understanding of the physical limitations and negative consequences of large-scale biofuels cultivation and consumption that are only now starting to receive due attention. This paper presents a physical evaluation of key characteristics of liquid transportation fuels across the domains of physics, chemistry, biology, and economics, and highlights the deficiencies that preclude biomass from becoming a primary energy source and biofuels from replacing petroleum as a national-scale transportation fuel. These factors include fatal petroleum-dependence, poor energy return on investment (EROI), low energy density, abysmal power density, huge water footprint, demonstrable food competition regardless of feedstock, increased environmental damage, promotion of land confiscation and human rights violations, and the supreme irony of increased lifecycle greenhouse gas (GHG) emissions. This paper argues that biofuels do more to harm the causes of national and global security than to help them.

Key Words: biofuel, military, energy, strategy, policy, EROI, ethanol, biodiesel, water footprint, greenhouse gas, nitrogen, ammonia, fertilizer, nitrous-oxide, carbon dioxide, photosynthesis, biodynamics, desalination, power density

Section 1: Introduction

"Good public policy however requires good scientific analytical evidence on the risks and the opportunities of different kinds of technologies and development choices."

–UN Environmental Programme[1]

About 1200 AD in the coastal region of the Andes in what is today northern Peru, the Chimu Empire faced a severe water shortage during a prolonged drought. In a flurry of public works activity that greatly stressed the royal treasury, the government embarked on a crash program to construct a 50-kilometer canal to bring water to the people. Construction was started simultaneously on several parallel routes in hopes that one of them would pay off. A great expenditure of labor was made to erect sections of aqueduct as high as 30 meters and to waterproof miles of earthen trenches with tile. However, the evidence is that this grand waterworks project never delivered water to the capital city of Chan Chan. Modern surveys of the ruins have found a fatal flaw that doomed the work—the canal route has segments that run uphill.[2]

Unfortunately, there are similarities between Chimu engineering and the current reckless pursuit of biofuels. Both were begun without a proper survey of the terrain and obstacles, both have taken approaches that attempt to defy unyielding physical laws, and both have expended prodigious resources without achieving their goals. The Chimu tried to make water run uphill in defiance of the law of gravity. The US government and military are trying to make energy run uphill in defiance of the laws of thermodynamics.

There is a set of talking points trumpeted almost daily in the press to justify biofuels as an essential part of US energy strategy. Some prominent figures and pundits argue that biofuels will increase our domestic supply of transportation fuel, end our dependence upon foreign oil, reduce military vulnerabilities on the battlefield, and generally improve national security. Biofuels are further promised to reduce fuel price volatility, reduce polluting emissions, reduce greenhouse gases, and even stimulate the economy. These arguments all fall apart under scrutiny. The promise and curse of biofuels is that they are limited by the energy that living organisms harvest from the sun. They suffer from a fatal catch-22: uncultivated biomass produces biofuel yields that are far too small, diffuse, and infrequent to displace any meaningful fraction of US primary energy needs; and boosting yields through cultivation consumes more additional energy than it adds to the biomass. Furthermore, the harvested biomass requires large amounts of additional energy to upgrade it into the compact, energy-rich, liquid hydrocarbon form that is required for compatibility with the nation's fuel infrastructure, its transportation sector, and

especially its military. When the energy content of the final product biofuel is compared to all the energy that was required to make it, the trade proves to be a very poor investment, especially in consideration of other alternatives. In many cases, there is net loss of energy. When energy balance (energy output minus energy input) across the full fuel creation and combustion lifecycle is considered, cultivated liquid biofuels are revealed to be a modern-day attempt at perpetual motion that is doomed by the laws of thermodynamics and a fatal dependence upon fossil fuel energy. Biofuels' promise of energy security also proves to be an illusion as their price is more volatile and supply less assured, being subject to the economic and political vagaries of both the international energy markets and agricultural markets, as well as the whims of weather.

This paper focuses on cultivated biomass converted into liquid transportation fuel, and all references to biofuels throughout should be taken to refer to these circumstances unless specified otherwise. The overall approach is an analysis of alternatives comparing four distinct biofuels methodologies with conventional petroleum fuel to assess their relative costs and benefits. It begins by first considering what energy security means in terms of fuel quality and supply. Then it builds an analytical framework of key parameters and shows how each of the biofuel methodologies fall short. It then provides evidence that the pursuit of biofuels is doing irreversible harm to the environment, increasing greenhouse gas emissions, undermining food security, and promoting abuse of human rights. In short, this paper finds that the United States cannot achieve energy security through biofuels, and that even the attempt is ironically achieving effects contrary to "clean" and "green" environmental goals and actively threatening global security. It concludes with specific recommendations for policy and action.

Section 2: Failing to Learn the Lessons of History and Current Science

Scientists have been looking at alternatives to petroleum fuels for over a century. The first commercial cellulosic ethanol plant in the United States opened in 1910 and failed after WWI.[3] In World War II, Germany synthesized diesel fuel from coal and the Japanese distilled turpentine from tree roots for airplane fuel. They both did this, not for any economic or performance advantage, but in desperation because Allied bombing and tanker sinkings had deprived them of petroleum. The US government spent $87 million between 1944 and 1953 on synthetic liquid fuel research involving military testing before dropping the program due to uncompetitive economics.[4] The Department of Energy (DoE) in 1977 focused research intently on ethanol as vehicle fuel. In 1980, in spite of record high oil prices, DoE formally abandoned the "Gasohol" program after acknowledging that physical limits of poor energy balance and extreme land use requirements made it impractical.[5] DoE also spent $25 million investigating microalgae under the "Aquatic Species Program" between 1978 and 1996, and $458 million on its "Biofuels Program" during that same period before shutting them down without achieving any breakthroughs.[6] The billions being spent today on entrepreneurial start-ups by the US federal government and military acting as venture capitalists are largely covering the same ground with the same result. Even advanced technologies such as genetic engineering cannot produce life forms that violate basic laws of physics and biology which will be discussed below.

Since 2008, a new generation of rigorous studies across the full spectrum of biofuels has been published that consider the full fuel production and consumption lifecycles at commercial scale, as well as the impacts of converting land to biofuel crop production. These studies have dramatically undermined the naïve assumption that biofuels are inherently clean and green, carbon-neutral, and America's ticket to energy self-sufficiency. But these watershed scientific documents have so far had little impact on US government or military energy policy. The US Navy directly rejected a RAND National Defense Research Institute study conducted at the direction of Congress and delivered to the Secretary of Defense in January of 2011 that unambiguously found biofuels of "no benefit to the military."[7] A second RAND study and a report by the US National Academy of Sciences that both severely questioned the wisdom and efficacy of current US biofuels policies also resulted in no adjustments to Environmental Protection Agency (EPA) or Department of Defense (DoD) biofuels programs.[8] In August 2012, the German National Academy of Sciences, of a country very aggressive in its pursuit of alternative energy, released the report of a 3-year study that concluded biofuels offer little or no benefit in reducing GHG emissions, and that "the larger scale use of biomass as energy source is not a real option for countries like Germany." The German scientists even went so far as to flatly recommend that all of Europe

abandon their biofuel production mandates.[9] In October 2012, the National Research Council released a report which severely questioned the feasibility of algae-based biofuels and highlighted five areas of major concern that parallel and support arguments made in this paper against all cultivated biofuels.[10] These are but a few of the studies that point out critical and fatal flaws in pursuing biofuels as a substitute for petroleum, and this paper draws from scores more. Only if policy-makers are willing to roll up their intellectual sleeves and examine the tedious details do they have a chance to craft strategies grounded in realistic probabilities rather than baseless hopes. An effective energy strategy for the United States must be informed by history and exploit rather than defy the laws of nature in order to increase global stability and US security. It is important for all to approach this topic with a shared understanding of the relevant science, technology, and terminology.

An effective energy strategy for the United States must be informed by history and exploit rather than defy the laws of nature in order to increase global stability and US security.

Section 3: The Science of Energy

3.1. Some Terms of Reference

Energy is a quantity of heat or work and can be measured in *joules*. A *primary energy source* is something obtainable from the environment that can be used directly for heat or work, or be made into a *fuel*. Candidates include crude oil, natural gas, coal, geothermal steam, uranium, wind, solar radiation, waves and tidal currents, food crops such as corn and sugarcane, cellulosic crops such as wood and switchgrass, and oil-yielding organisms such as soy and microalgae. An *energy carrier* is something that stores and transports energy for release under controlled circumstances. Examples include flywheels, electrical storage batteries, compressed gas, water collected behind a dam, and especially the chemical bonds of specific atoms such as hydrogen and carbon. Chemical energy carriers are generally packaged together with other non-energy carrier substances that make them easier to store and handle and consume. The resulting tailored combination forms a *fuel* that may be suitable for use within a given living or inorganic system, such as glucose for a plant or animal, or gasoline for an internal-combustion engine. *Combustion* is the chemical reaction of burning a fuel with oxygen (usually from ambient air) to release energy. *Power* is the rate at which energy is produced or consumed and can be measured in *joules per second*, otherwise known as *watts*.

The US Congress has authoritatively defined *energy security* in Title 10 of US Code as "having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet mission essential requirements."[11] In 2011, the United States imported 45% of its petroleum, and this fraction generates concern because of dependence upon other nations for supply and unpredictable global market price volatility.[12] If there exists a way to reliably supply US transportation energy exclusively from domestic sources with reasonable and stable prices, it would clearly enhance energy security. Advocates argue that every gallon of domestic biofuel is one less gallon of dependence upon foreign oil, and that producing enough biofuel will achieve oil independence and allow the United States to pull back its military forces from protecting the Persian Gulf. While it is a dubious proposition that current geopolitics and globalized energy markets and US relationships with international partners would allow for military disengagement from the Middle East, this paper does not challenge the argument on those grounds. Rather it is the first assumption that biofuels can substitute for and displace petroleum fuels that is the core issue addressed.

3.2. Basic Thermodynamics

An energy strategist must understand two unbreakable laws of the universe. The first law of thermodynamics (*conservation of energy*) essentially states that energy obeys the rules of checkbook math. The energy balance of a system, like the balance of a checkbook, is the sum of all deposits and withdrawals, and the withdrawals cannot exceed the deposits. Energy is not magically created from nothing nor does it disappear; it only moves between things or changes form. The second law of thermodynamics (*entropy*) distinguishes between two kinds of energy: useful energy that can perform work and useless energy that cannot. It holds that some fraction of useful energy irreversibly becomes useless energy every time energy is converted from one form to another. In other words, entropy is like an ATM fee that must be paid on all transactions. The bank of the universe deducts some percentage of every energy deposit, withdrawal, or conversion into its own account, leaving less as the customer's spendable balance. Together, these two laws declare that the amount of useful energy that can be recovered from a system is always less than the energy that was input into the system. This is why it is impossible to construct a perpetual motion machine. The more complex a process is in the number of steps and transformations required, the more usable energy will be lost along the way.

3.3. The Chemistry of Hydrogen, Carbon, and Nitrogen

The hydrogen atom is a principal energy carrier in many chemical fuels because it is abundant, is very reactive in accepting and releasing energy in its chemical bonds with other atoms, and is the lightest element, giving it a very high *gravimetric energy density* (joules per kilogram). Hydrogen gas (H_2) is a fuel of pure energy-carriers that can power everything from micro-organisms to turbine engines.

Carbon is another lightweight element with very high combustion energy that is an excellent energy carrier and fuel component. Carbon also has another highly desirable quality in that it readily forms long molecular chains and can serve as a backbone to organize many other atoms into dense and neatly organized packages–not unlike the plastic rings that hold six-packs of soda cans together. When it comes to hydrogen, carbon is a chemical miracle worker. Combined with hydrogen in equal parts it forms highly versatile and energetic liquid fuels. Higher carbon ratios yield solids and lower ratios yield gases. Carbon also performs the trick of packing hydrogen atoms together much more closely than they will tolerate on their own. This is why gasoline actually contains 63% more hydrogen atoms per gallon than pure liquid hydrogen does.[13] Because carbon also adds its own significant energy to the mix, gasoline has 3.5 times the *volumetric energy density* (joules per gallon) of liquid hydrogen. The addition of carbon transforms hydrogen from a diffuse and explosive gas that will only become liquid at -423°F, into an easily-handled room temperature liquid with more than triple the energy density

and ideal volatility characteristics for a combustion fuel. If we didn't have carbon, we would have to invent it as the ideal tool for handling hydrogen.

Nitrogen, like carbon, also tightly packages hydrogen energy carrier atoms together to make an efficient fuel. One nitrogen atom bonds with three hydrogen atoms to form ammonia (NH_3). This combination of nitrogen and hydrogen is a potent organic fuel for most bacteria and plants, which have the ability to metabolize it directly or with each other's symbiotic help.[14] This fact is vitally important to properly understanding the role of ammonia-based fertilizers.

3.4. The Chemistry of Agriculture

A typical green plant contains more hydrogen than any other element—46 of 100 atoms are hydrogen, 32 are carbon, 21 are oxygen, and less than 1 in 100 is nitrogen.[15] Carbon and hydrogen store energy in plants in the form of various sugars and sugar polymers generically referred to as carbohydrates, and as lipids (fatty oils). Hydrogen ions and their liberated electrons are the fundamental energy currency of plant and animal metabolism.[16] One quarter of the combustion energy of typical plant biomass is in the hydrogen fraction, even though it constitutes only 6% of the dry weight. The remaining 75% of the energy is in the 50% carbon mass fraction. The nitrogen and oxygen fractions actually reduce the combustion energy density of the biomass.[17]

Carbon dioxide ($CO_{2)}$ and water (H_2O) are the raw materials of photosynthesis, and they supply the carbon and hydrogen atoms, but they supply no energy. These compounds are the end-products of combustion, and their carbon and hydrogen are already depleted of all the free energy they carried. Plants, algae, or microbes must perform the chemical magic of "un-burning" CO_2 and H_2O and reforming their hydrogen and carbon back into carbohydrates and lipids that can once again power organic metabolism and support combustion. This requires the input of huge amounts of energy.[18] The attractive theory of biofuels is that all this energy can come for free as photons from the sun. However, the devastating limiting-factor for all biofuels is that photosynthesis captures solar energy with surprisingly poor speed and efficiency—only about 0.1% of sunlight is translated into biomass by the typical terrestrial plant,[19] and this translates into an anemic power density of only 0.3 watts per square meter (W/m^2) in the optimal conditions of the cloudless US southwest.[20] This is 20 times worse than the 6.0 W/m^2 that current solar panels arrayed in large farms can collect from the same sunlight and acreage.[21] Power density will be discussed in detail in its own section below, but the key point here is that the limiting factor for biomass growth is not just the availability of CO_2 and water, but the availability of input energy. Fortunately, plants have another avenue besides the sun to collect energy—the soil.

Carbon dioxide and water are the raw materials of photosynthesis, but they supply no energy.

Placing ammonia in the soil to fuel plant growth is known as "nitrogen-fixing."[22] This is done naturally through animal urine and manure, by the decay of protein matter from once-living things, by lightning, and through the action of symbiotic soil and root bacteria using photosynthesis energy borrowed from their host plant.[23] An historical look at crop records reveals that US corn farmers reached the limits of photosynthesis and natural nitrogen-fixing by the turn of the 20th century, and yields plateaued at 30 bushels per acre for a generation until another way to pump energy into plants was adopted.[24]

3.5. Giving Nature a Helping Hand

In 1909, Fritz Haber discovered the chemistry of converting natural gas into ammonia—i.e., converting fossil fuel into plant fuel. This allowed the creation and mass-production of modern ammonia-based artificial fertilizers with many times the potency of mineral salt and bio-waste fertilizers. His discovery so revolutionized agriculture that he won the 1918 Nobel Prize. The United States began to widely adopt ammonia-based fertilizers in the 1940s. Today's ultrahigh-yield crops have been bred and genetically engineered to pull much of their energy from artificially boosted soil ammonia rather than depending exclusively upon the sun and natural nitrogen-fixing. To provide this artificial plant fuel, the world converts massive amounts of natural gas into ammonia each year. The manufacture of ammonia is second only to plastics in consumption of US industrial energy,[25] and 86% of that ammonia goes into fertilizer.[26] Wherever "nitrogen" is used in the context of fertilizer today in the United States, it is almost certainly referring to ammonia. Virtually 100% of the 28 million metric tons of "nitrogen" fertilizer used each year are ammonia formulations.[27] An institutional pre-occupation with nitrogen and a lack of appreciation for ammoniacal hydrogen in evaluating the energy balance of plants and fertilizers is likely one of the principal reasons why the deficiencies of biofuels are not readily recognized by many agricultural professionals. It is largely because of this conversion of fossil fuel energy into food that humanity has avoided Robert Malthus' 1798 prophecy of global famine from population growth overtaking food production.

It is largely because of the conversion of fossil fuel energy into food that humanity has avoided global famine.

Without artificial fertilizer, crops grow much more slowly and yield far less per acre than we have become accustomed to in the modern world. The largest yield of corn in the United States prior to ammonia fertilization was 31.7 bushels per acre in 1906.[28] Today, Iowa farmers pump pure liquid ammonia into the soil at the rate of 150-200 lb/acre to harvest consecutive annual crops of 160-180 bushels per acre of corn—a six-fold increase.[29] The amount of sunshine flooding an acre of Iowa cropland has not changed since 1906. Rather, five-sixths of the increase in the modern corn harvest is attributable to altered genetics and improved intensive farming efficiencies that take advantage of hydrogen and nitrogen energy artificially

placed in the ground in massive quantities by humans. US Department of Agriculture historical data show that corn yields were flat through two generations of hybridization and farming innovation and mineral nitrogen fertilization following the civil war, but exploded beginning in the early 1940s when ammonia plants built to make explosives for the war effort began also to supply ammonium nitrate fertilizer for agriculture (Figure 1).[30] Choosing not to artificially fertilize with ammonia would send corn yields plummeting back toward their natural 1906 value and greatly increase the needed land acreage for the same harvest.[31]

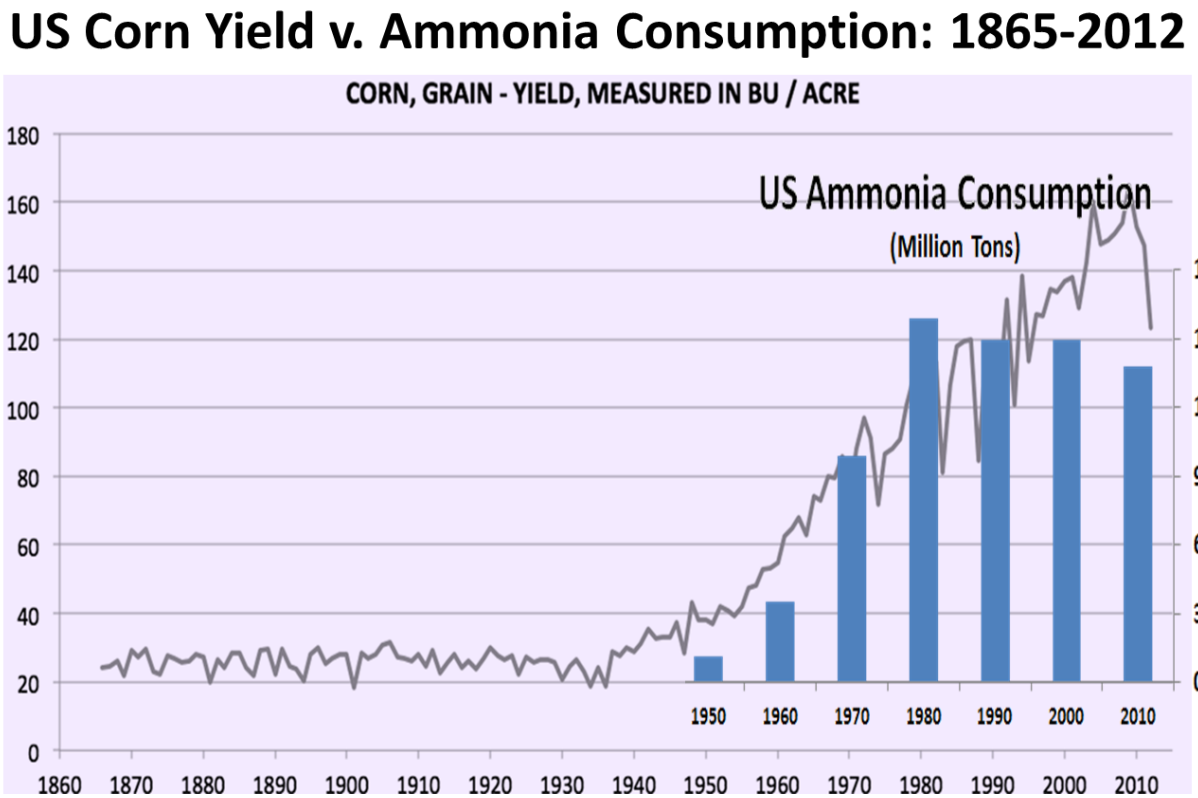

Figure 1. US Corn Yields and Ammonia Consumption

Despite emphatic claims from snake oil salesmen who use terms like "drought-loving" when they mean "drought-tolerant," all crops must obey the laws of thermodynamics and can only yield energy output in biofuel significantly less than the energy input to grow them. Switchgrass, jatropha, miscanthus, and other species that are often claimed to thrive in marginal circumstance, only produce the high yields promised in the investment brochures when benefiting from liberal application of water and fertilizers and herbicides and pesticides as is duly noted in published research. For example, switchgrass takes as long as 30 years to fully develop on unmanaged land as part of a natural prairie biome, and 3 years to produce a full yield even as a cultivated monoculture—and it depletes soil nutrients like any other vigorous crop.[32] Without boosting from artificial fertilizers, meaningful annual yields of biofuel crops are not sustainable. There is no free

lunch. India is one of many countries where farmers have recently been victimized by promises of miracle crops only to be ruined by results that were an order of magnitude lower.[33]

3.6. Summary of the Science

Whether discussing fossil fuels or biofuels, the combustion energy is in the hydrogen and carbon. Those who advocate a transition to a "hydrogen economy" fail to appreciate that our world (organic and industrial) already runs on a hydrogen economy–one enabled by carbon and nitrogen. Thermodynamics and chemistry teach us that we reduce the usable energy content of a primary energy source with every step of converting it to a fuel. Biology and physics show that photosynthesis places a cap on the natural power density of biofuels that limits them to yields which are far below other alternatives (and which will be shown to be far below the minimum that modern civilization requires). To overcome the solar-limit on biomass production for food crops, humans have figured out how to input fossil fuel energy in the form of ammonia fertilizers. While this is a justifiable option to increase food production, it makes no sense to add energy to something that is supposed to be an energy source such as biofuel crops. It is also nonsensical to add fossil fuel energy when the objective is to reduce the use of fossil fuels. It is even worse to do this knowing that the process of converting fossil fuel energy into biomass is hugely wasteful of energy. Before proclaiming which energy sources will supply America's future needs, energy strategists must understand the demand side of the equation in terms of both quantity and quality.

Section 4: The Fuel Needs of Modern Civilization

4.1. The Petroleum Standard

The US population and economy consume more than 102 exajoules of energy a year (exa = quintillion). More than 1/4 of this energy—28 exajoules—is consumed as liquid combustion fuels used for transportation (i.e., gasoline, diesel, avgas and jet fuel). A perfect combustion fuel possesses the desirable characteristics of easy storage and transport, relative inertness and low toxicity for safe handling, measured and adjustable volatility for ready mixing with air, stability in its characteristics across a broad range of environmental temperatures and pressures, and—of critical importance—high energy density. Because of sweeping advantages across all these parameters, liquid hydrocarbon fuels refined from petroleum have risen to dominate the global transportation economy and ushered in a jet age and space age that would not exist without them. Conventional diesel, jet fuel, and gasoline are the gold standards for transportation fuels.

Liquid hydrocarbons are the gold standard for transportation fuel and have singularly enabled the jet age and space age.

Any candidate to replace refined petroleum has quite a high bar to vault in terms of physical performance. The list of candidates with superior volumetric energy density is short and comprises only solids.[34] Fuels derived from biomass are markedly inferior in performance. Biodiesel is not a hydrocarbon but a cocktail of fats cut with alcohol that tends to solidify in cold temperatures. Ethanol is even further from a hydrocarbon and is corrosive to pipelines and vehicle fuel systems. Pyrolysis bio-oil is a highly acidic and chemically unstable brew of over 300 different organic compounds. All three biofuels contain oxygen, are more soluble in water, and are more conductive of electricity than hydrocarbons, all of which promote the contamination and corrosion of fuel systems. The physical characteristics of all three make them incompatible with the world's huge capital investment in petroleum storage and pipeline infrastructure, greatly restricting their availability and utility.[35] They all have lower energy density than their hydrocarbon counterparts. Moving a given quantity of energy around a battlefield as biodiesel instead of petroleum diesel would require 8% more tanker trucks, ethanol or bio-oil 65% more, liquid hydrogen 280% more. Substituting biobutanol, biogas, ammonia, fuel cells, capacitors, or batteries in place of hydrocarbons on the battlefield would require even longer convoys that expose more Soldiers and Marines to enemy attack, not fewer.[36] Increasing fuel efficiency of military equipment or buying fuel locally are the only ways to reduce convoys.

4.2. Hydrotreated Biofuels

To overcome all the above limitations and make biofuels into the "drop-in" replacement fuels that are fully compatible with existing fuel infrastructure and military and civilian engines, their alcohols and lipids and mystery molecules must be transformed into true hydrocarbons by a complex series of processes collectively known as *hydrotreatment*. These chemical manipulations increase the ratio of hydrogen to carbon, remove all oxygen, and change the structure and blend of the constituent molecules to give the fuel its necessary characteristics.[37] Hydrotreatment greatly increases the cost, reduces the energy benefit, and undermines claims of renewability for the resulting fuels because it requires the addition of fossil fuel hydrogen derived from natural gas and releases 11 tons of CO_2 for every ton of hydrogen added. A national security energy strategist must understand these technical but vital details and also be aware that *all military aircraft and combat vehicles and civilian airline fleets can only use hydrotreated biofuel* even as additives and blends of conventional fuels. Besides all the inherent performance advantages of hydrocarbon fuels, there is an even more fundamental reason why refined petroleum fuels dominate.

Section 5: Energy Return on Investment

For energy strategists to get the right answers, they must first ask the right questions. When choosing a primary energy source and a fuel to derive from it, it is essential to be sure the fuel will meet the demands of the civilization that will consume it. Raw primary energy sources require some energy to be consumed to process them into finished fuels. One key measure of a fuel's usefulness to civilization is how much useful energy it yields as fuel divided by how much energy was required to extract the primary energy source from the environment and convert it into that fuel. This metric is known as *energy return on investment* (EROI).[38]

$$\text{EROI} = \frac{\text{Energy usable in newly produced fuel}}{\text{Energy consumed in producing the new fuel}}$$

An EROI of 1:1 would mean that the useful energy in a newly produced quantity of fuel is exactly equal to the energy consumed to produce it. It might seem that any EROI greater than unity is of net benefit to civilization–but this is false. A modern civilization requires a much greater return on its investment than this because survival and standard of living depend upon the size of this margin. To help quantify what civilization requires of its energy sources, it is helpful to look at how the laws of physics apply to living organisms.

5.1. Civilization Is a Living Organism

Dynamic Energy Budget (DEB) theory is a sophisticated approach to looking at living things in terms of energy.[39] A thermodynamic analysis reveals that any organism can only afford to expend a small fraction of its current energy stores finding and processing new primary energy sources into fuel (*assimilation*) because there are many other essential energy-consuming (*dissipation*) tasks it must perform to survive; these include sustainment, repair, protection, maturing and increasing in complexity, and reproduction. Only if there is surplus energy after all of these demands are fully satisfied will the organism increase its mass (*growth*). To power all these activities, the organism needs food that is not just fractionally positive in net energy, but rather has an EROI many multiples greater than unity. A civilization is itself a high-order physical and biological organism that has tremendous overhead costs and can spare only a fraction of its energy to assimilate new energy. One researcher exploring the linkage between physics and economics has found an historical linear relationship between global civilization's accumulated

physical mass (i.e., net value of accumulated capital) and its appetite for energy, with a value of 9.7 milliwatts per 1990 US dollar.[40] This same approach also revealed a similar linear relationship between civilization's wealth and the amount of CO_2 it exhales.[41]

Furthermore, this econo-physics research and the theory of biodynamics both support a concept in conventional economics called "Jevon's paradox," which holds that increasing energy efficiency *increases* energy demand. This counterintuitive outcome is due to the difference between living things and machines: a living organism that adapts to use its quota of food more efficiently will gain more body mass and thus increase its appetite for food. This behavior was first observed in patterns of steam engine improvements and coal use by William Stanley Jevons in 1865, and is an historically-validated truth that throws a huge wrench into policy-makers' efforts to control global warming GHG emissions by legislating efficiency improvements. Efficiency gains are observed to raise standard of living rather than reduce consumption. This is not to say efficiency is a bad thing–it also makes an organism more competitive in a resource-constrained environment. However, efficiency and conservation are two distinct phenomena. Conservation (i.e., reduced consumption) is a response to resource scarcity and higher prices. Civilization, like all living things, is stubbornly biased toward growth and never voluntarily leaves food on the plate. Understanding Jevon's paradox also allows one to detect that many of the predicted trajectories of atmospheric CO_2 are likely too low because they wrongly apply energy efficiency corrections. Energy strategists must realize that civilization is a living organism, not a machine, and apply the correct principles of biology and economics and physics to make accurate predictions and effective policies.

5.2. EROI of Ancient Civilization

EROI is a function of both the energy profit inherent in a primary energy source and the efficiency of prevailing technology in converting that energy profit into fuel and then into work output. An insightful historical analysis of the construction of the Roman Colosseum yields data from which one may calculate an EROI for the grain-based economy of first century Roman civilization.[42] At peak efficiency, humans and oxen fueled by organically cultivated wheat and alfalfa were capable of delivering a maximum EROI of 4.2:1 calculated as the ratio of their output physical work to the input of crop farming resources and labor necessary to feed them. In the course of the five-year construction of the Colosseum, the Romans actually achieved an EROI of approximately 1.8:1 due to various practical limitations including 145 no-work holidays a year.[43] Western civilization's EROI dropped during the Middle Ages as the Empire's enormous and efficient *latifundia* crop plantations disappeared.

Rome's peak was only surpassed 1,700 years later when steam engines were developed that could extract high EROI work from coal, ushering in dramatic increases in standards of living, and ultimately helping industrializing nations to

move away from dependence upon draft animals and slaves. Later, petroleum's high EROI, higher energy density, and extreme versatility enabled the transportation revolution of aircraft and rockets. To appreciate the magnitude of this energy revolution, consider that three tablespoons of crude oil contain the equivalent of eight hours of human labor, and a car's tank of gasoline contains approximately two man-years of energy. An average American household benefits from the equivalent of hundreds of virtual servants in the form of the heat and electricity and transportation it enjoys courtesy of hydrocarbon fuels. It is clear that the energy-hungry cars, washing machines, air conditioners, and airplanes of modern civilization can only be sustained with higher EROI fuel than that available to Rome, but the question is, how much higher?

5.3. EROI of Modern Civilization

A study of historical US economic performance over the last century has found that recessions are linked to overall fuel EROI dipping below a critical threshold of 6:1.[44] This value represents the minimum energy quality civilization must have to sustain a modern, energy-intensive quality of life. Another macro-analysis found that an EROI of 3:1 is the bare minimum quality a raw energy feedstock must have to overcome all production costs and conversion losses and still deliver any positive net energy to modern civilization.[45] To put these values in biological terms, a modern post-industrial civilization is very energy-hungry, and if undernourished on a diet of fuels with lean EROIs below 6:1, becomes catabolic: eating into the fat of its savings and the muscle tissue of its infrastructure to replace the missing calories. As long as EROI remains below 6:1, industrial civilization is locked into a death spiral where an ever increasing fraction of its economic output (GDP) is spent on energy at the cost of an eroding standard of living.[46] In economic terms, this exactly describes what is commonly known as a recession, or, more accurately, a contraction. At EROIs below 3:1, the fuel is so poor that digesting it takes more energy than it returns, and full starvation sets in. The only way out of this hunger trap is either to find higher EROI energy, or to decay into a pre-industrial civilization with lower energy needs.

A modern economy slips into recession if net fuel EROI drops below 6:1, and starves if EROI drops below 3:1.

The bottom line is that the economy of a modern developed nation slips into recession if its net fuel EROI drops below 6:1, and starves if EROI drops below 3:1. The inevitable consequence if such low EROIs persist is industrial collapse and regression of civilization to agrarian-age economics (Figure 2). Purposely displacing high-EROI energy sources with anything that returns less than 6:1 is to foolishly and harmfully push economies toward recession and civilization toward regression. It will have the same effect as starving a human with a diet of hay. Plotting out primary energy source and fuel EROI estimates versus their current energy contribution to the US economy provides a useful perspective on their relative utility (Figure 3).[47]

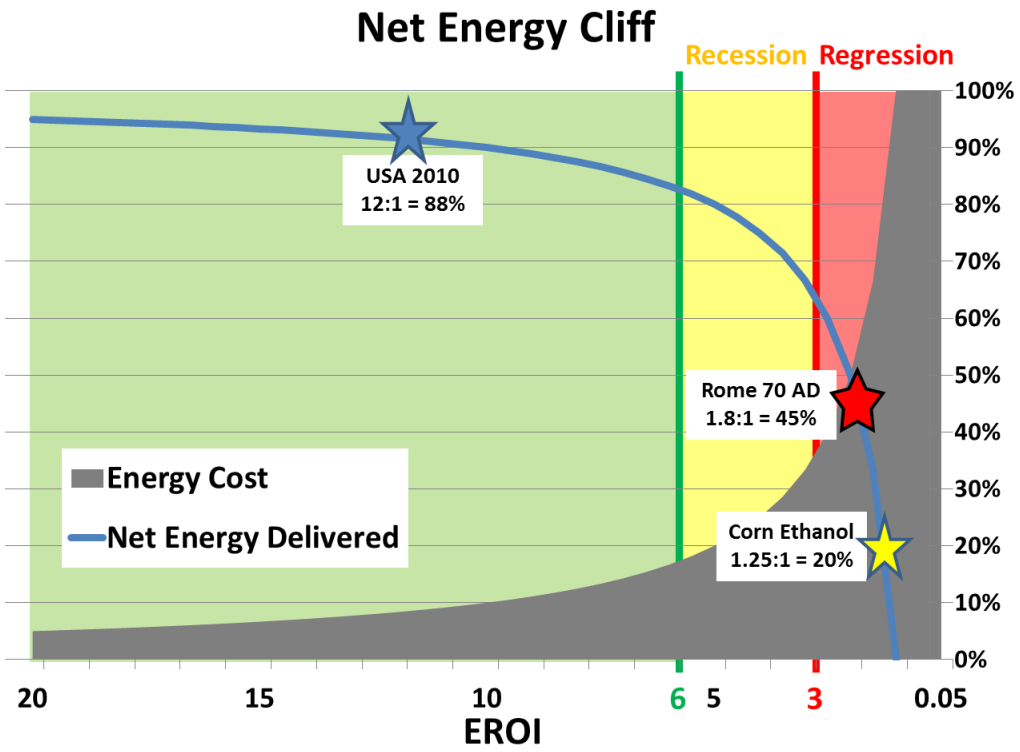

Figure 2. Net Energy Cliff

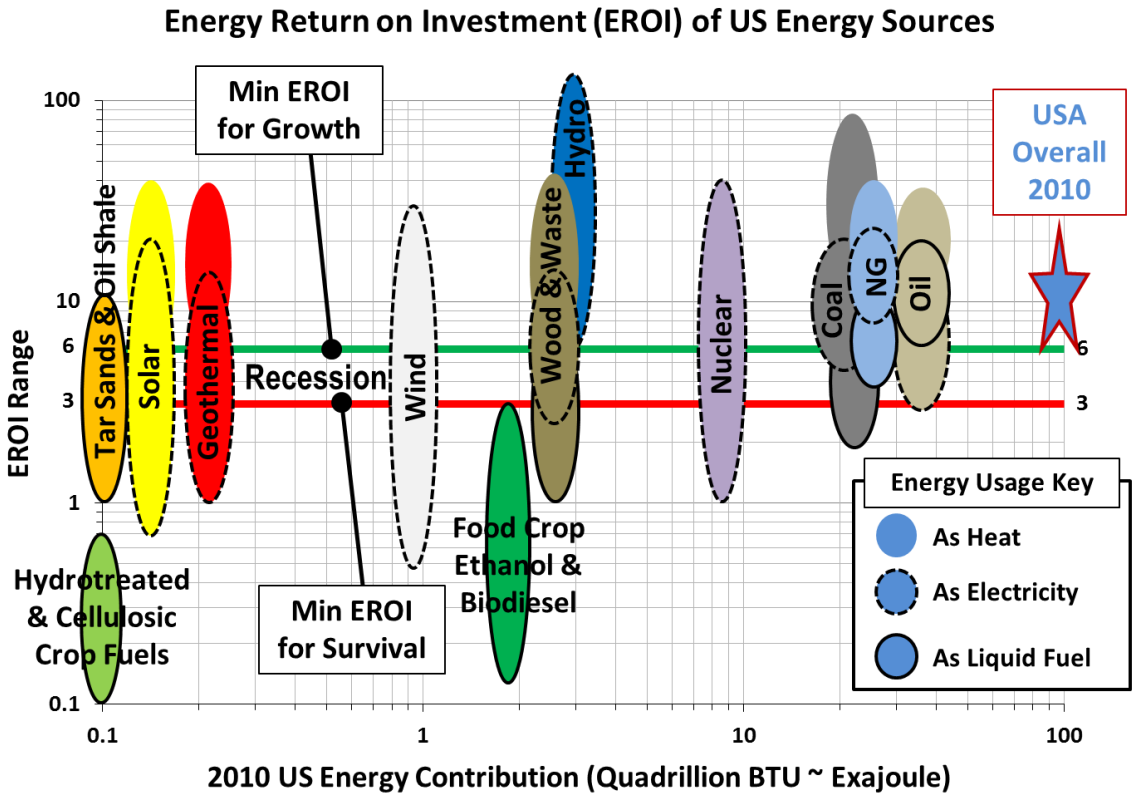

Figure 3. Energy Return on Investment (EROI) of US Energy Sources

Section 6: Evaluating Biofuels

6.1. Food Crop Ethanol

Over the past 70 years, the United States has nearly perfected corn as a high-yield food and industrial starch feedstock. The conversion of corn kernel starch to ethanol has been optimized, yielding nearly 500 gallons per acre per year. Unfortunately, corn's dependency upon fossil fuel and the thermodynamic penalties paid for even this relatively easy biofuel transformation is such that, after decades of study and experimentation and continuously refined commercial production, the scientific literature consensus for corn ethanol EROI is a lowly value of 1.25:1.[48] Even worse, there is no net gain in liquid fuel energy—the produced ethanol contains energy barely equal to the input fossil fuel energy. The small energy profit is contained in a high-protein byproduct of distillation called "distillers' dry grains and solubles" (DDGS) that can supplement animal feed. The stark reality is that more than $6 billion a year in annual direct federal assistance to corn growers and ethanol refiners since 2005 has served only to reduce a non-existent foreign dependence on animal feed.

Billions of dollars in corn ethanol subsidies have served only to reduce a non-existent foreign dependence on animal feed.

Sugar beet and sugarcane are more expensive feedstock for ethanol than corn in the United States and Europe, but a bit simpler to convert into ethanol.[49] A spectacular 8:1 EROI for Brazilian sugarcane is often cited, but examination of the calculations reveals that this is a different computation known as External Energy Ratio.[50] When the huge internal energy cost of burning cane straw (bagasse) for distillation heat energy is properly counted, the EROI corrects to less than 2:1 in line with US and European figures.[51] The cane is first burned in the field to remove leaves, trash, and rodents, and then the bagasse left after crushing out the sugar is burned for heat to distill the fermented ethanol. The entire process is hugely damaging to air quality, and bagasse-fired sugar and ethanol refineries smoke like 19th century steel mills.[52] The myth of Brazilian sugarcane ethanol is further deflated by recently declining crop yields due to unsustainable farming practices. Yields per hectare fell 18% in the 2011-2012 season due to depleted soil and pest damage, and the government was forced to respond by lowering the gasohol blending ratio last October from 25% to 20% and by *importing* 1.2 billion liters of ethanol.[53] New sugar-ethanol plant construction in Brazil peaked at 30 in 2008 and is now down to near zero. Ethanol use there appears to have plateaued, and though it is not yet well known, US ethanol production just peaked this year as well and is projected to fall in 2013.[54]

Corn and sugarcane, along with other cultivated food crops such as sugar beet and sweet sorghum, represent the most productive of biofuel feedstocks in terms of fuel yield per acre. Farmed seaweed (macro-algae) has the potential to join but not surpass this group with further technology development. The relatively high fraction of easily processed sugars and starches in these crops is precisely why they are cultivated for food—and fuel. Nevertheless, their yields without cultivation are too low to serve as significant energy sources, and their EROIs as cultivated crops are nowhere near high enough to keep America's economy out of recession.

6.2. Cellulosic Ethanol

Cellulose and lignin are super-strong sugar polymers that form the bulk of green plant structure such as stalks, stems, trunks, blades, and branches. Cellulose forms the interlocking fibers that provide tensile strength, while lignin is the cell wall armor plating that provides rigidity and compression strength. These materials are much harder to digest into food or fuel than the easy starches and sugars of food crops. Evidence of the intrinsically poorer fuel feedstock quality of lignocellulose is apparent in biological metabolism. A human can live on a starchy corn kernel diet, but will starve eating corn stalks or cellulosic grass without the four-chambered stomach of a cow and the devotion of all waking hours to grazing and chewing cud. Lignin is so chemically stubborn that the only practical way to retrieve chemical energy from it is to burn it as a solid directly for heat. Cellulose can be broken down into fermentable sugars, but must first be separated from the lignin. Paper manufacturers have been working this problem for centuries and have found no better alternative than a combination of concentrated acid and explosive steam treating known as the "Kraft process." However this one step alone consumes as much energy as exists in the final ethanol. Those who want to make a liquid fuel out of lignocellulose must use much slower and more expensive enzyme or microbe-assisted processes to have any hope of preserving some net energy. After separation, pure cellulose (same solid material as cotton fiber and cellophane) must be further broken down into component sugars by tons of water and truckloads of yeast and designer enzymes (most likely synthesized from petroleum feedstock). Then there still remains the very energy- and water-intensive separation, distillation and dehydration steps to reduce the 4% alcohol "beer" solution to 99.5% pure anhydrous alcohol that can be added in small quantities to gasoline without voiding manufacturer warranties. To make a fully substitutable motor or jet fuel, alcohols can also be hydrotreated, but at even more energy loss and expense than biodiesel.

A rigorous thermodynamic analysis has predicted cellulosic ethanol to be three or more times more difficult to produce than food crop ethanol, with lower yields and with an EROI far below 1:1.[55] However, a much-touted USDA study that assumed away many of the known difficulties and costs to predict a fancifully EROI for switchgrass of 5.4:1 (four times better than corn ethanol) is the more often-cited paper, and has been used to justify spending billions of dollars in federal and private funds on some high-profile entrepreneurial misadventures.[56] However, the

proof is in the performance. Despite all the subsidies and tax breaks and fuel mixing mandates emplaced and accelerated since 2005, the National Academy of Sciences recently acknowledged that there is not a single commercially viable cellulosic ethanol facility in the United States today.[57] Rather, the landscape has been rocked by high-profile collapses such as the demise of Range Fuels, signature creation of vocal biofuels proponent Vinod Khosla and recipient of the first USDA biofuels loan guarantee of $64 million in 2010.[58] This failure eclipsed the 2009 fraud scandal and implosion of Cello, which was the Solyndra of cellulosic ethanol. As of the writing of this paper, ZeaChem Inc., founded in 2002 and recipient of $297.5 million in grants and loan guarantees from the DoE and USDA, is operating its 250,000 gallon per year biorefinery in Oregon as a demonstration facility, which means the product is not commercially competitive.[59] Shell has spent almost $400 million on cellulosic ethanol at Codexis with no commercial progress to show for it.[60] BP and KiOR and others have recently cancelled or suspended or delayed construction of huge cellulosic bio-refineries in the United States.[61] Instead of the 500 million gallons of cellulosic ethanol that huge cumulative subsidies and guaranteed markets were promised to deliver by 2012,[62] the EPA officially counts only one commercial transaction to date—a 20,069-gallon sale of Brazilian sugarcane bagasse ethanol from Blue Sugars Corporation's demonstration facility to an undisclosed buyer last April.[63] Some of the companies who've been working on cellulosic ethanol the longest such as Gevo, Amyris, and Cellana, have shifted to corn ethanol, industrial chemicals, and fish food.[64] Around the world, cultivated food crops (corn, sugarcane, soy, palm, and various oilseeds) account for all statistically significant liquid biofuel production.[65] Nevertheless, the EPA continues to fine US oil refineries for not mixing non-existent cellulosic ethanol into their gasoline.[66]

Instead of the 500 million gallons a year promised, total commercial cellulosic ethanol production to date is 20,069 gallons.

Two new cellulosic ethanol biorefineries have recently started operations and their performance in the coming months should be revealing. In the fall of 2012, KiOR opened a 10 million gallon-per-year biorefinery in Mississippi that investors and the EPA have been promised will deliver commercial sales and profits from competitively-priced gasoline and diesel made from trees. INEOS Bio likewise commissioned an 8 million gallon-per-year commercial cellulosic ethanol plant in Florida. However, expectations for these massive capital investments are already being deflated by relabeling "commercial" to "commercial demonstration" or "second generation demonstration," and shifting profitability target dates to future years. Even if these plants somehow achieve marginal profitability with a stacked deck of biofuel subsidies and blending mandates and carbon taxes, they will still face an insurmountable capacity challenge because of abysmal power density, as will be discussed shortly. Meanwhile, some of the companies who've been working on cellulosic ethanol the longest such as Coskata and Primus Green Energy are quietly leading a mass migration away from any pretense of renewable fuels, to instead boldly embrace synthetic liquid fuels made from cheap natural gas.[67] In the end, even the enzymatic and microbial processes entail large net energy losses with

an EROI far below 1:1 for cultivated biomass. To find out exactly how bad the numbers are, one would have to ask people like the former CEO of Codexis, who has publically confessed that making hydrocarbons from carbohydrates is a dead end, and who is now at Calysta working on natural gas-to-liquid fuel.[68]

6.3. Biodiesel

A third option, besides growing a plant for its starches or cellulose, is to grow it directly for oil. Species which yield some biomass as lipids include soy, camelina, rapeseed, oil palm, jatropha, peanut, sunflower, cottonseed, safflower, and microalgae. All of these crops, including a non-poisonous Mexican variant of jatropha, have provided human and animal food over the centuries. The natural lipids in these plants can be broken down by adding methanol (made from natural gas) to convert them into a soup of fatty-acid methyl esters (FAME)–commonly known as "biodiesel." Lipid fractions of plants are generally small compared to starch fractions, and that is why soy biodiesel yields per acre are much smaller than corn ethanol yields (70 gal/acre v. 500 gal/acre) and consume so much more water per liter of fuel, as will be discussed later.[69] Soy Biodiesel EROI calculated from rigorous, full commercial-scale lifecycle studies is slightly better than corn ethanol at 1.9:1, but still nowhere close the 6:1 threshold for minimal utility.[70] The well-known oil fraction limitation of terrestrial plants is why there has been 80 years of research on fast-growing, higher lipid fraction micro-algae as a way to get a high-yield biodiesel crop.[71]

Algae is the only biodiesel crop with high enough potential yields to replace US petroleum without consuming all US territory as cropland, so it is worth a detailed look. All plants, including algae, stubbornly want to produce carbohydrate structural biomass instead of lipids because that is how they grow and reproduce. Lipids are an intermediate synthesis product that are only accumulated in larger amounts when the plant is starved of some essential nutrient such as nitrogen or silicon essential to complete biosynthesis of new structural biomass. Lipid yield in g/m^2 of pond or bioreactor surface area is a function of the number of algae cells and their individual lipid fractions. Absolute yield is limited because one can either starve the algae to produce more oil or feed them to foster reproduction, but not both—another *catch-22*. [72] In addition, lipid fraction controls buoyancy for algae. It cannot be increased beyond the point where the algae float to the surface, crowd out the sunlight, dry out, and die. These are physical and biological limits known from previous research under the Aquatic Species Program. It is not possible to change basic physical laws such as Archimedes' principle of buoyancy with even the most sophisticated genetic engineering.

Additionally, attempts to move algae from the lab bench to commercialization continue to be crushed by poor EROI. A literature survey of reported algae EROIs performed by the National Research Council found values from 0.13:1 to 7:1, but in the higher cases, energy credits from co-products dwarfed the energy delivered as biodiesel—biodiesel was really the co-product and solid biomass the product.[73] If

there is any benefit and profit to be made from algae, it appears to be more in producing soylent green than in producing green fuel. A critical look at the more optimistic studies that predict the higher EROIs reveals that they depend upon a host of unrealistic assumptions—massive supplies of free water and nutrients, a free pass on enormous environmental impact, and market economics that miraculously transform the huge burden of enormous accumulations of soggy byproduct biomass that has per-ton value less than the cost of transportation into a cash commodity crop. Proponents often claim that algae need only sunlight and CO_2 to grow. However, to make the high yields promised, fertilizer energy is typically supplied in the nitrogen, carbon, and hydrogen molecules of a solid form of ammonia called urea.[74] Solazyme Inc., the US Navy's choice for algae biofuel and recipient of a $21 million DoE biorefinery grant,[75] actually grows their product in dark bioreactors, feeding it carbon and hydrogen energy in the form of sugar. This makes them unique in producing a biofuel 100% dependent upon a food crop and getting 0% of its energy from the sun via direct photosynthesis—a worst case scenario.[76]

The most realistic, full-scale, full commercial lifecycle studies find a break-even 1:1 EROI if the algae biomass is simply sun-dried and shoveled directly into a furnace for heat.[77] Any attempt to convert to liquid fuel results in a large negative energy balance. Hydrotreating further destroys EROI, as can be seen in prices paid by the US Navy for algae biofuels below. The simple but decisive math is that, even at commercial scale, with generous assumptions about cellular reproduction rate and lipid fraction and oil extraction, and ignoring the costs of facilities and water, Argonne National Laboratory calculated that it takes 12 times as much total energy and 2.6 times as much fossil fuel energy to put a gallon of non-hydrotreated biodiesel in a gas station pump instead of a gallon of petroleum diesel.[78]

6.4. Fast Pyrolysis Bio-Oil

One byproduct of the Kraft process discussed above that paper companies use to separate cellulose from wood is "tall oil" or "pine oil." An alternative *fast pyrolysis* process uses heat, catalysts and in some cases solvents to maximize the production of "bio-oil" from wood feedstock instead of the separation of cellulose. Fast pyrolysis is able to convert up to 70% of the feedstock wood into bio-oil. However, the product oil is far inferior in its engine compatibility to even ethanol without extensive reprocessing and hydrotreatment. Raw bio-oil has about the same energy per gallon as ethanol, but each gallon is 50% heavier.[79] Its formula is highly variable depending upon the specific process temperatures, pressures, catalysts, solvents, and filtration, as well as what plant species is the feedstock of the moment. Bio-oil has been tested to contain over 300 different compounds in varying proportions including acids and metals. It has a high ash content, high moisture content, high oxygen content, low volatility, low overall quality, and a typical pH of 2.0-3.0, which is so acidic that special stainless steel is needed for processing.[80] It also has a very limited shelf life in that it rapidly polymerizes into a viscous semi-solid. Processes are still being developed to filter out the ash and

metals and to stabilize shelf life, but all the steps required to transform bio-oil into a reasonable petroleum substitute promise a very poor EROI.

As with algae, economic viability depends upon being able to monetize leftovers and byproducts into lucrative commodities, and being given an environmental pass—in this case on unprecedented massive commercialization of forest land. Fast pyrolysis typically produces large volumes of organic-laced wastewater that must be treated, and the major co-product is "bio-char," which is a term of art for charcoal powder. Bio-char is touted as a soil "conditioner" and carbon sequestering mechanism, but its benefits are completely overshadowed by the soil acidification and N_2O GHG emissions of nitrification if any ammonia fertilizer is used for the feedstock crop.[81] Bio-char also presents considerable handling challenges as it is a flammable powder that is explosive and toxic when airborne. EROI is poor because much of the original feedstock combustion energy is lost in the pyrolysis process and more is carried away in the unused bio-char at the rate of 30 million joules per kg.[82] Synthetic gas is also a co-product, but is generally fully consumed onsite to augment the bio-char, natural gas, or other sources of heat used to drive the pyrolysis process.

Economic viability of algae biodiesel and pyrolysis bio-oil depends upon being able to monetize byproducts into lucrative commodities.

If fast pyrolysis magically converted 100% of tree energy into liquid fuel energy with zero thermodynamic losses, the power density of the process, without boosting with fossil fuel fertilizers, would be limited to the photosynthesis limit previously discussed of 0.3 W/m2. Under these ideal conditions, satisfying the nation's transportation fuel needs of 28 exajoules per year would require harvesting the annual growth of 731 million acres of trees, which happens to be about the exact total of forest in all 50 states.[83] If all 800 species of trees in all 750 million acres of biodiverse US forest habitat were replaced with fast-growing monocultures of pulpwood that mature in 25 years, the United States would have to fell 30 million acres of trees a year for pyrolysis transportation fuel. When adjusted for actual yields and EROI of a realistic fast-pyrolysis process at scale, the required acreage goes up by many multiples. Numbers like these are why many environmental organizations including a nine-nation European consortium have begun to come out strongly against biofuels.[84]

Section 7: Fuel Lifecycles and Opportunity Cost

Direct comparison of competing alternatives is a sound evaluation technique and introduces the important economic concept of *opportunity cost*. Not only should new fuels have an EROI greater than 6:1 as a threshold criteria, they should also have a competitive EROI equal to or greater than available alternative fuels suitable to the same purpose. If they have a lower EROI, and their use is compelled, their production will parasite energy from higher EROI fuels and their use will be an energy sink to the economic sector they serve.[85]

7.1. Fossil Fuel versus Corn Ethanol

Current petroleum diesel and gasoline production EROIs are variously estimated between 10:1 and 20:1.[86] Taking a conservative approach least favorable to petroleum, this paper will postulate an 8:1 EROI for purposes of comparative analysis, which represents the lowest ebb of crude oil calculated since 1920.[87] An 8:1 EROI means that 1 barrel of liquid petroleum fuel energy input[88] can support the exploration, drilling, extraction and refining of enough crude oil to make 8 new barrels of liquid petroleum fuel energy—which happens to come with a bonus of 1 barrel of chemical feedstock for plastics, lubricants, organic compounds, industrial chemicals, and asphalt (See Figure 4).[89] The much lower 1.25:1 EROI of corn ethanol means that, to produce the same net gain of 8 barrels of energy requires *not 1, but 32 barrels* of input energy. And for ethanol, the output energy profit is delivered not as liquid fuel, but as 5.5 tons of animal feed co-product. The 52 barrels of lower energy-density, lower compatibility, and more corrosive ethanol produced as the primary product contain just enough energy to make up for the 32 barrel-equivalents of fossil fuel energy used to make them, and deliver no net energy gain. The dramatic difference between this picture and what one finds in biofuels advocacy propaganda is fourfold. Firstly, this view portrays the whole fuel creation and consumption lifecycle instead of just a misleading combustion-only comparison of a barrel of oil versus a barrel of ethanol. Secondly, it holds energy output as the constant between the two cases, because civilization demands energy, not barrels or bushels. Thirdly, it balances mass and energy inputs and outputs as is required by the laws of thermodynamics. Fourthly, it demonstrates the essential economic concept of *opportunity cost*—in this case how a given amount of invested energy can deliver wildly different outputs of usable fuel depending upon the path taken.

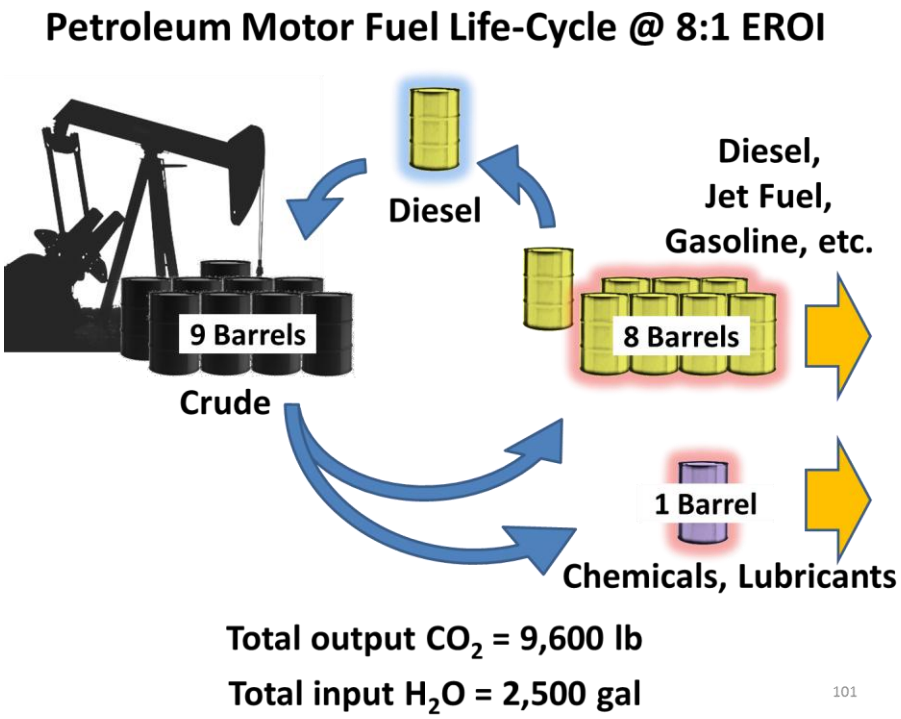

Figure 4. Petroleum Motor Fuel Lifecycle

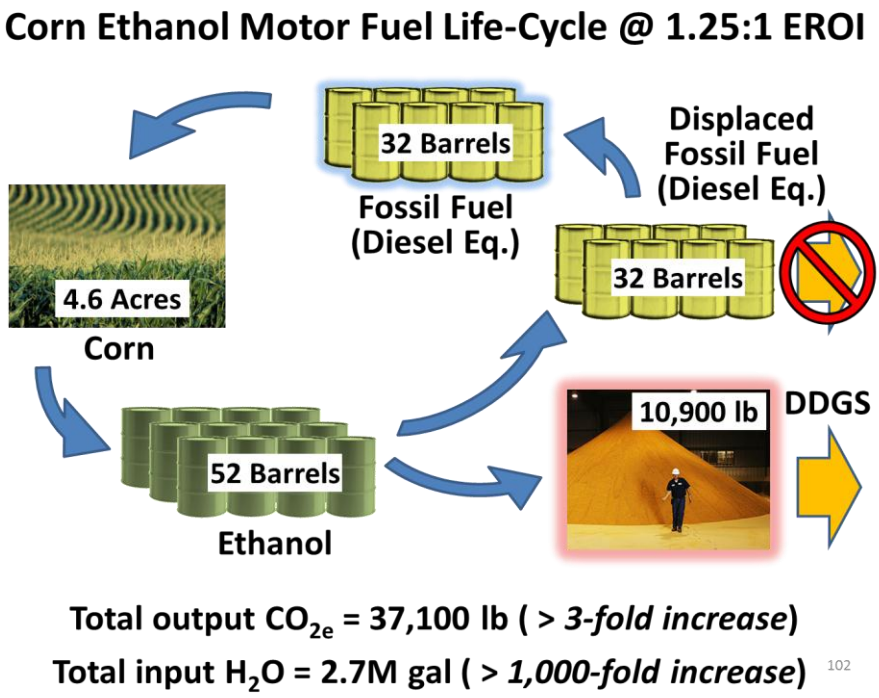

Figure 5. Corn Ethanol Motor Fuel Lifecycle

To summarize the corn ethanol fuel lifecycle depicted in Figure 5, it is the transformation of 4.7 tons (180 gigajoules) of high-quality fossil fuel and 11,000 tons of fresh water into 7.2 tons of lower-quality ethanol fuel-additive (180 gigajoules) and 18.5 tons of CO_{2e}, all for the net energy output of 5.5 tons of animal feed.[90] From the perspective of opportunity cost, one barrel of fossil fuel energy can either deliver 340 pounds of animal feed or 2,200 pounds of refined petroleum fuel (336 gallons, 1 metric ton), and the latter with lower lifecycle GHG emissions and much lower water use. Compared to the petroleum fuel lifecycle (Figure 4), the corn ethanol fuel lifecycle (Figure 5) consumes 3.5 times more fossil fuel, more than triples GHG emissions, increases water use by three orders of magnitude, adds environmental costs from agriculture while still suffering those associated with fossil fuels, and competes with food cultivation for the necessary land acreage and other agricultural production capital and resources. If high-protein animal feed supplement is the object, the much more efficient and economical path generally chosen by US farmers in the absence of ethanol subsidies is growing soy, which fixes its own nitrogen and has 49% protein content vice 27% for DDGS.[91]

The investment of one barrel of fossil fuel energy can either deliver 340 pounds of animal feed or 1 metric ton of refined petroleum fuel.

7.2. Parasitic Dependence and Hybrid EROI

This comparative EROI methodology can be applied to other biofuels as well. It shows that lower EROI fuels (e.g., corn ethanol) drag down the overall average and multiply rather than reduce the consumption of higher EROI fuels (e.g., refined petroleum). Civilization's demand for energy is the constant that must be met. Lower EROI fuels, by definition, require a higher investment of energy upfront to deliver the same energy output as higher EROI fuels. Biofuels can only truly substitute for fossil fuel fuels when the EROIs of both converge, and this cannot happen if the former is an energy parasite of the latter. Biofuels in the United States are not displacing fossil fuels, they are accelerating their use. The only way to displace imported petroleum, and thereby improve national security, is to domestically produce fuels with higher EROI than refined petroleum. Any such fuel will be instantly adopted because the evidence of its higher EROI will be a lower price.[92]

It is also important to understand that the corn ethanol EROI discussed above and those published in the literature are not for a pure corn ethanol lifecycle, but for a hybrid lifecycle involving both fossil fuel and corn ethanol, where fossil fuel provides much of the input energy. A proper corn ethanol EROI would be calculated using corn ethanol and sunlight as the exclusive energy sources to make more corn ethanol. This author could find no example of corn ethanol (or any biofuel) being used as the exclusive energy source for making more of itself, and the reason is easy to deduce. Knowing the EROI contribution of the external fossil

fuel inputs and the overall EROI of the hybrid process, it is possible to derive the internal EROI of processing corn into ethanol. Dividing the 1.25:1 hybrid EROI by the 8:1 fossil fuel EROI yields a corn ethanol EROI of 0.156:1 = 1:6.4. Thus, making ethanol from corn is a negative energy balance process that consumes more than five-sixths of the energy invested.[93] The US economy would get six times as much usable energy from the same investment of fossil fuel energy if it was used to produce refined petroleum instead of being diverted to making ethanol and DDGS. Modern intensively-farmed corn, with its huge appetite for fossil fuel energy, is making a large net negative contribution to the nation's energy budget and thus working to increase rather than decrease fossil fuel demand. This is a trade we might justify for corn used as food, but it is an indefensible choice for corn converted into fuel.

What is true for corn ethanol is true for all cultivated crop biofuels. Natural gas and crude oil supply the vast majority of the hydrogen and carbon used to make fertilizers, pesticides, herbicides, farm machinery fuel, biorefinery process heat, the designer enzymes and bulk organic chemicals needed by some advanced processes, the hydrotreatment hydrogen gas discussed earlier, and a good portion of the electrical energy involved. The parasitic dependence of cultivated crop biofuels upon fossil fuels precludes any chance of them reducing dependence upon foreign oil, assuring domestic supply, or making prices less volatile. Without fossil fuels or a replacement source for massive quantities of hydrogen to make ammonia, all biomass yields—including food—will plummet toward what they were before Haber's discovery in 1909, with devastating consequences for the world.[94] Accelerating the use of fossil fuels by foolishly and wastefully using them to make much lower EROI biofuels brings any day of future fossil fuel scarcity that much closer and is completely counterproductive to every "clean" and "green" energy goal. Applying ammonia fertilizer to any crop intended for biofuel is an indefensible waste of energy.

Section 8: Energy and Economics

8.1. Markets and Price Volatility

Liquid biofuel prices are already as volatile as oil prices and track up and down with the international oil market.[95] The recent drought in the US midwest caused a corn price spike that already has forced the shutdown of many ethanol refineries and is jeopardizing fuel blending mandates.[96] Deriving fuel from farming does not liberate it from petroleum dependence or oil market price volatility, but rather increases price volatility by adding an additional linkage to global agricultural commodities markets. Energy security is reduced by choosing a primary energy source that has no proved reserves, but rather is created from scratch annually and is subject to floods, freezes, droughts, and blight. In the final analysis, biofuels are constrained by thermodynamics and the limits of photosynthesis to be niche fuels for those few in the world uniquely blessed with surplus fertile land and free water, and who have pre- or post-industrial power needs that can be met with low power density and unpredictably variable energy. This excludes the mining, manufacturing, electric utility, construction, and transportation sectors that are the *sine qua non* of modern civilization. Biofuels are simply not suitable to be national primary energy sources for developed nations, and less so for the exploding populations and meager budgets of developing nations. They are even less suitable for military forces, whose needs are more intensive and inflexible.

Energy security is reduced by choosing a primary energy source that has no proved reserves, but rather is created from scratch annually and is subject to floods, freezes, drought, and blight.

8.2. Peak Ethanol

Even before this year's drought, US corn ethanol production had been following a trajectory that should be familiar to disciples of Dr. Marion King Hubbert (see Figure 6).[97] Annual production totals of corn ethanol plot a perfect "Hubbert curve," rising from virtually zero in 1980 to peak this year at less than 15 billion gallons.[98] Dr. Hubbert was a petroleum industry geophysicist who in 1956 famously predicted what has become known as "Peak Oil." His prediction was based on observations of US crude oil production that had historically followed an exponentially increasing slope, but in 1952 hit an inflection point where the rate of growth started to slow. Hubbert fit a mathematical curve to the data and predicted

that US oil production would peak between 1965 and 1970—and in 1970 his prediction came true. He explained his empirical observations with the rational theory that oil was a non-renewable, finite resource that gets progressively more difficult to find and extract as the amount is depleted. Rates of discovery would eventually slow and be overcome by the increasing difficulties of extraction, and production would peak when half of the extractable oil had been pulled from the ground.

However, if growing scarcity is all that drives a Hubbert curve, why do we see one for corn ethanol, a *renewable* resource? It is because there are additional factors—international competition, market share, carrying capacity, the decreasing energy-intensity of developed nations transitioning to services-based economies—that powerfully affect production of any fuel, renewable or otherwise. In the case of corn ethanol, Hubbert's peak would seem to indicate that supply has caught up with demand, and its subsidized surge to become a rival of gasoline is culminating at a value suspiciously coincident with the refinery blending market guaranteed by the EPA's Renewable Fuel Standard (RFS).[99] Interestingly, US oil production rebounded in the 80's in response to oil company capital investment in the 70's, and is rebounding again now in response to a surge of capital expenditures since crude prices started up in 2003. The lesson here for energy strategists is that there is danger in accepting one-dimensional explanations for observed behavior, and even more danger in relying exclusively on those simplistic explanations to make predictions. There is also a lesson for policy-makers about the inability of even massive subsidies to overcome underlying thermodynamic and economic weakness.

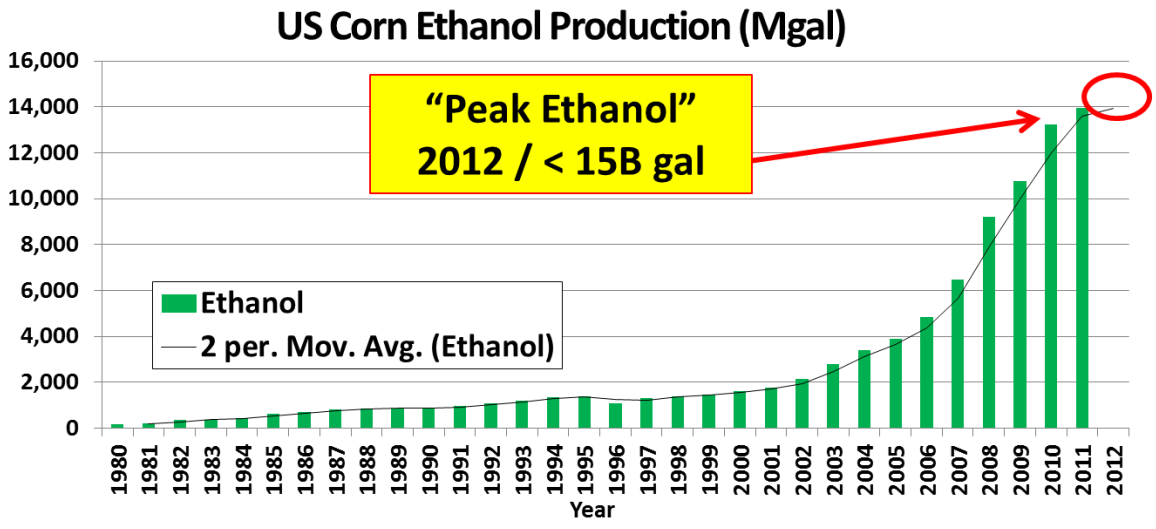

Figure 6. US Peak Ethanol

Section 9: The Real Cost of Biofuels

The huge gap between biofuel prices and petroleum fuel prices is directly linked to the similar disparity in their EROIs (compare Figure 1 and Table 1). High EROI fuels have lower costs and lower prices that allow both the fuel producer and the fuel consumer to profit because of low overhead and large margins. Low EROI fuels have higher costs and prices that leave both producer and consumer with little or no room to prosper.[100] Subsidies can mask the truth of EROI, but cannot change it. This is shown by the performance of biofuels enterprises when the subsidies run out, and by the transitory nature of the green jobs associated with those plants. According to a Washington Post analysis of DoE funding data, $17 billion disbursed by the federal government on green energy stimulus projects as of September 2009 had created less than 4,000 permanent jobs, with tens of thousands of temporary jobs disappearing once the money was spent.[101] Economies of scale work when margins are small but positive. However, when EROI is upside-down, scaling up just digs a bigger hole. In the case of new energy candidates such as biofuels, transition from research and development to deployment is harmful if it has not yet attained a lifecycle EROI of better than 6:1, and is not commercially viable unless it has attained an EROI competitive with the national average and other energy source alternatives (i.e., approximately 12:1 today per Figures 2 and 3). Below these thresholds, the energy candidate can only survive as a cash and energy parasite of government subsidies and higher-EROI energy sources.

9.1. The Military's Cost

One of the core goals of the DoD's new *Operational Energy Strategy* is to reduce military energy costs so that the Department can "shift resources to other warfighting priorities, and save money for the American taxpayers."[102] The civilian leadership of the US Navy is often heard quoting the statistic that a $1 rise in the cost of a barrel of oil increases annual fuel costs by $31 million.[103] Yet, the cheapest price the Navy has paid for any biofuel to date is $1,080.66 per barrel ($25.73 per gallon).[104] Since 2007, the military has spent $67.8 million on 1.35 million gallons of biofuel, averaging more than $50 a gallon or $2,100 a barrel, and costing the taxpayers $60 million more than if conventional fuel had been purchased (Table 1).[105] This does not include more than $47 million paid for pure research on alternative fuels. Based on the most recent government contract prices, a US military service secretary has the following

The cheapest price the US Military has paid for any biofuel to date is $25.73 per gallon.

Table 1: Department of Defense Fuel Purchases

DoD Biofuels Purchases						
Date	**Contract**	**Vendor**	**Fuel**	**Gallons**	**$ Total**	**Per Gallon**
Aug 2009	SP0600-09-D-0519	Sustainable Oils	Camelina JP-5	40,000	2,664,000	**$66.60**
Aug 2009	SP4701-09-C-0040	Solazyme	Algae F-76	20,055	8,574,022	**$427.53**
Sep 2009	SP0600-09-D-0518	Solazyme	Algae JP-5	1,500	223,500	**$149.00**
Sep 2009	SP0600-09-R-0704	UOP (Cargill)	Tallow JP-8	100,000	6,400,000	**$64.00**
Sep 2009	SP0600-09-D-0520	Sustainable Oils	Camelina JP-8	100,526	6,715,137	**$66.80**
Jun 2010	SP0600-09-D-0519	Sustainable Oils	Camelina JP-5	150,000	5,167,500	**$34.45**
July 2010	SP0600-10-D-0489	Sustainable Oils	Camelina JP-8	34,950	1,349,070	**$38.60**
Aug 2010	SP0600-10-D-0490	Sustainable Oils	Camelina JP-8	19,672	759,339	**$38.60**
Aug 2010	SP0600-09-D-0520	Sustainable Oils	Camelina JP-8	100,000	3,490,000	**$34.90**
Aug 2010	SP0600-09-D-0517	UOP (Cargill)	Tallow JP-8	100,000	3,240,000	**$32.40**
Sep 2010	SP4701-10-C-0008	Solazyme	Algae F-76	75,000	5,640,000	**$75.20**
Aug 2011	SP4701-10-C-0008	Solazyme	Algae F-76	75,000	4,600,000	**$61.33**
Sep 2011	SP0600-11-D-0526	Gevo	Alcohol to JP-8	11,000	649,000	**$59.00**
Sep 2011	SP0600-11-D-0530	UOP	Bio JP-8	4,500	148,500	**$33.00**
Nov 2011	SP0600-11-R-0705	Dynamic Fuels (Tyson, Syntroleum, Solazyme)	Tallow & Algae JP-5 Tallow & Algae F-76	100,000 350,000	12,037,500	**$26.75**
Feb 2012	N68936-12-P-0209	Albemarle	Cobalt n-Butanol to Jet Fuel	55	245,000	**$4,454.55**
Sep 2012	SP0600-13-D-0452	Amyris	Sugar F-76	18,000	463,140	**$25.73**
Sep 2012	SP0600-12-D-0561	Gevo	Alcohol JP-8	45,000	2,655,000	**$59.00**
DoD Synthetic Fuels Purchases						
Jun 2007	SP0600-07-D-0486	Equilon	Natural Gas to Aviation Kerosene	315,000	1,075,694	**$3.41**
Jun 2008	SP0600-08-D-0496	SASOL	Coal to Aviation Kerosene	60,000	225,000	**$3.75**
Jul 2008	SP0600-08-D-0497	SASOL	Coal to Aviation Kerosene	335,000	1,306,500	**$3.90**
Sep 2009	SP0600-09-D-0523	PM Group	Natural Gas to Diesel	20,000	140,000	**$7.00**
DoD Bulk Contract Conventional Fuel Purchases						
FY 2010	Various		JP-8 Jet Fuel	2,296M	5,201M	**$2.26**
			JP-4 / Jet A-1	1,249M	2,884M	**$2.31**
			JP-5 Jet Fuel	541.8M	1,175M	**$2.17**
			F-76 / Diesel	805.7M	1,816M	**$2.25**
			Motor Gasoline	70.7M	174.1M	**$2.46**
FY 2011	Various		JP-8 Jet Fuel	2,079M	6,478M	**$3.12**
			JP-4 / Jet A-1	1,246M	4,032M	**$3.24**
			JP-5 Jet Fuel	529.3M	1,572M	**$2.97**
			F-76 / Diesel	875.9M	2,590M	**$2.96**
			Motor Gasoline	59.0M	186.6M	**$3.16**

purchase options for jet fuel: $3.24 per gallon for conventional Jet A-1/JP-4 petroleum jet fuel on bulk contract, $3.90 a gallon to SASOL for coal-based synthetic, $7.00 a gallon to PM Group for natural gas-based synthetic, $26.75 a gallon to Dynamic Fuels for Tyson chicken fat-based hydrotreated renewable jet (HRJ), $34.90 a gallon to Sustainable Oils for camelina HRJ, $59.00 a gallon to Gevo for isobutanol-based HRJ, $61.33 a gallon to Solazyme for algae HRJ, $4,454.55 a gallon to Albemarle for converting Cobalt n-butanol to HRJ, $11,248.99 a gallon to Honeywell UOP for converting Gevo isobutanol to HRJ.

9.2. The Nation's Cost

The per-gallon price paid by the military for biofuels is only a fraction of the federal government's full cost. Federal officials profess grave concern at the volatility of oil prices, and economic forecasters cite statistics that a $10 rise in the price of a barrel of oil slows the US economy 0.2% and kills 120,000 jobs.[106] Yet, the federal government is voluntarily paying more than $10 a barrel in biofuel subsidies (Table 2).[107] DoE pumped $603 million into biofuel refinery construction in 2010 as part of $7.8 billion in annual biofuels spending.[108] Now the Navy, at the direction of the President and in partnership with DoE and the Department of Agriculture, is funding another round of new bio-refinery construction while scores of failed bio-refineries are on the market today in bankruptcy fire sales (a Google™ search of "biofuel bankruptcy" returns an eye-watering list).[109] In the more than five thousand years that humans have been producing ethanol as wine and beer and distilled spirits, it has always been realized that all the invested labor and energy made the resulting products far too precious to use their alcohol fraction as a fuel. Only urban folk in the modern era, blinded by the ubiquitous wealth of fossil fuel energy, could fail to see the negative energy balance of using distilled liquor as a fuel at the cost of all the wood or gas or oil fuel used to distill it. Ethanol has inherent limitations that have made it a perennial loser as an energy source throughout the ages, unable to win market share from wood, olive oil, whale oil, coal, kerosene, petroleum, or natural gas. After 6 years of huge subsidies and blending mandates and guaranteed markets in the United States since 2005, a joule of corn ethanol energy today is still more expensive than a joule of gasoline energy. The American Automobile Association reports as of December 2012 that the mpg-corrected price of E85 ethanol at the gas pump is 40 cents a gallon higher than premium gasoline.[110] Because of EPA-mandated blending of lower energy density ethanol in gasoline, consumers in 2010 paid $8.1 billion at the gas pump for energy that was not put into their tanks.[111] When added to the $6.1 billion in federal subsidies given out the by US Treasury and taxpayers as ethanol tax credits, the US paid a $14.2 billion premium in 2010 to displace 6.4% of its gasoline energy with ethanol—and the cheaper gasoline that was displaced was exported.[112]

After 6 years of huge subsidies, a joule of corn ethanol energy today is still more expensive than a joule of gasoline energy.

9.3. The Nation's Gain

A true primary energy source, like a true food source, cannot be subsidized. It must, by definition, yield many times more energy (and wealth) than it consumes, or else it is a sink, not a source. Critics of "big oil" often claim it is subsidized, but when both sides of the balance sheet are considered, the money is revealed to be flowing the other way. All federal subsidies and tax breaks for oil and natural gas in 2010, as officially tallied across all government agencies and reported to Congress, totaled $2.82 billion, equaling 45 cents per barrel produced domestically.[113] Against that outlay, the federal government collected $56.1 billion in oil company corporate taxes and excise taxes on retail gasoline and diesel, equaling $9.01 per barrel—a 2,000% return.[114] State and local governments also collected similar shares in taxes and fees as well. It is not by subsidies, but rather by the merits of EROI and energy density and power density, and in spite of heavy taxation and fierce competition with other energy alternatives, that oil and gas have grown to dominate the global energy economy. Oil and gas are true primary energy sources that nourish rather than starve governments and economies. Global oil and gas is a $3.8 trillion industry that fully subsidizes 10 *rentier* petro-states and partially subsidizes the economies of 70 more oil exporting nations.[115] Just in the United States today there are 536,000 active crude oil wells, 504,000 active natural gas wells, dozens of continent-spanning pipelines, a colossal interstate highway system, 17 million barrels-per-day of refining capacity, 160,000 gas stations, and a $1.5 trillion fraction of the global oil and gas industry that have all been funded out of oil and gas EROI margins. The 1.5 trillion-dollar US share of the global oil and gas industry comprises 10% of the $15 trillion US economy.[116] Coal also has a high EROI, and together, fossil fuels provide 82% of US primary energy.[117] That fraction is a good approximation for the fossil fuel portion of the energy invested in making anything manufactured in the United States—including both food and biofuel.

Table 2: US Federal Government Energy Subsidies in 2010

US Federal Government Energy Subsidies in 2010			
Energy Source	***Federal Subsidies ($M)***	***Domestic Production (million barrels of oil equivalent)***	***Subsidy per barrel of energy produced***
Coal	1,358	3,793	$0.36
Oil & Gas	2,820	6,229	$0.45
Hydro	216	437	$0.49
Nuclear	2,499	1,451	$1.72
Geothermal	273	36	$7.63
Bio-mass/fuel	7,761	747	$10.39
Wind	4,986	159	$31.39
Solar	1,134	22	$52.30
Total	***21,047***	***13,921***	***Average = $1.63***

Section 10: Power Density and Capacity Limits

If EROI and price were not fatal enough, the question of ultimate capacity must also be answered. Land is a finite national resource with many competing uses. A recent European meta-study of 90 other studies found that only one-fifth of the world's energy demand could likely be met by biofuels without removing meat from the human diet or making massive land use changes beyond the 296 million acres that already must be added for additional food crops before 2050.[118] This is ultimately because biofuel production is a terribly inefficient use of land. This can best be illustrated with *power density*, a key metric for comparing energy sources.

10.1. Energy Sprawl

The 70 gallons of biodiesel per acre of soy and 500 gallons of ethanol per acre of corn are amazing agricultural achievements, but are dismal in terms of power density, and work out to be only 0.069 W/m^2 and 0.315 W/m^2 respectively. While corn is 4.5 times better than soy, it is a factor of 3 below wind (1.13 W/m^2), 19 times worse than PV solar (6.0 W/m^2), and 300 times worse than the 90 W/m^2 delivered by the average US petroleum pumpjack well on a 2-acre plot of land.[119] Thirty square meters of today's cheapest PV solar panels can capture the same amount of energy per year as is in the ethanol from 10,000 square meters (2.5 acres) of cultivated switchgrass.[120] This is coincidentally about the same amount of land the average American family would require as biofuels pasture for each of their cars. Alternatively, that land could sustainably grow crops to feed 20 vegans, or the crops and livestock to feed 2.5 meat-eating humans.[121] To replace the 28 exajoules of energy that the U.S. uses every year just for cars and trucks and airplanes would require more than 700 million acres of corn. This is 37% of the total area of the lower 48 states, more than all 565 million acres of forest, and more than triple the current amount of annually harvested cropland. Soy biodiesel would require 3.2 billion acres—one billion more than all U.S. territory including Alaska. Oil palm biodiesel yields are reported to be as high as 640 gal/acre (6,000 L/ha), which exactly doubles the power density of corn ethanol, but still falls far short of wind and solar power. As hinted earlier, algae biodiesel has the highest potential power density of any biofuel, but the best case predicted to ever be achievable at some date in the distant future, as

Algae biodiesel has the highest potential power density of any biofuel, but its predicted best-case future performance is equivalent to today's solar panels.

limited by physical laws and laboratory-perfect conditions, is 6.42 W/m^2—equivalent to what is produced today with PV solar panels at the solar farm on Nellis Air Force Base.[122] Figure 7 contrasts the land area of oil field, solar farm, wind farm, and corn field needed to replace the 2,000 MW of power produced by the San Onofre Nuclear Generating Station in Oceanside CA.

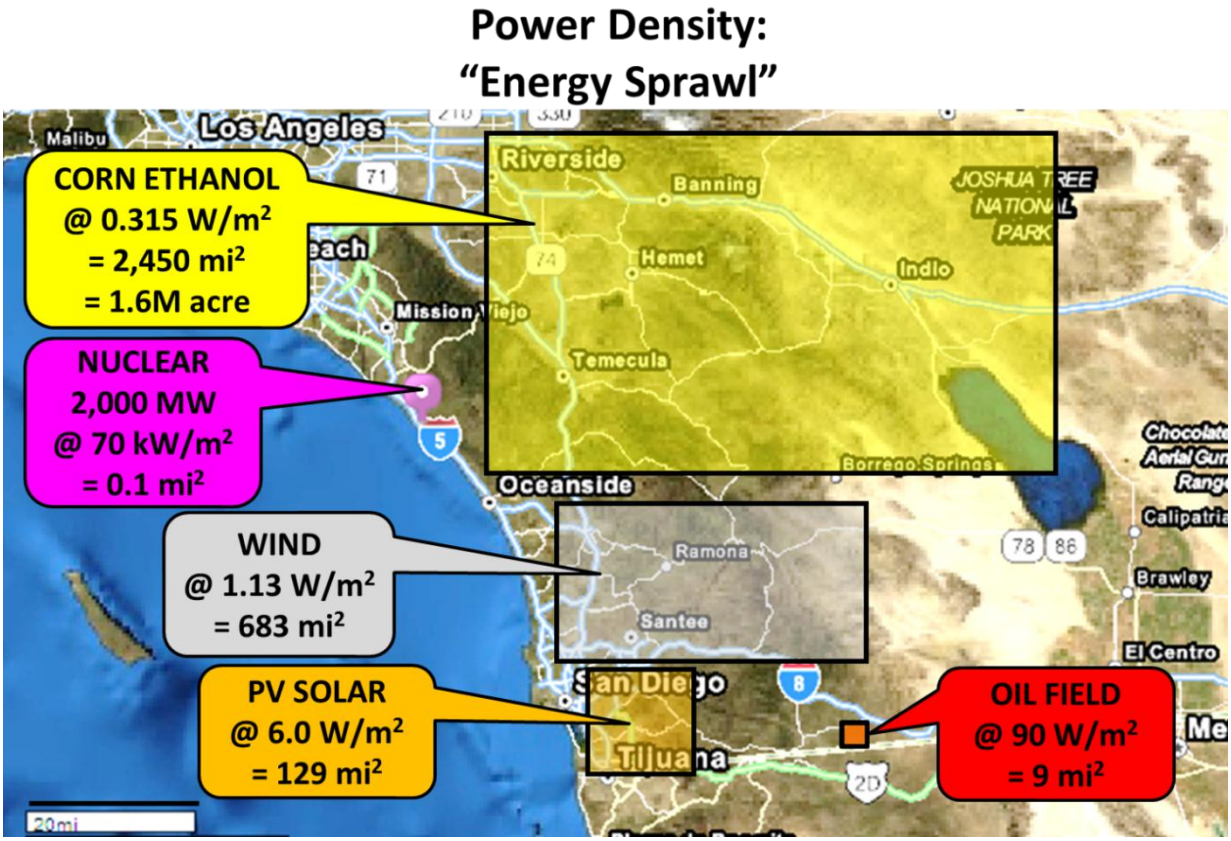

Figure 7. Power Density and "Energy Sprawl"

10.2. Green Grabbing

The USDA and DoE have explored the technical feasibility of channeling one billion tons of US biomass a year toward biofuels production.[123] However, their work discounts two very significant facts that undermine the positive conclusions. The first is that large amounts of cellulosic forest floor debris and cultivated crop residue stalks and leaves are not truly waste that can be harvested for fuel, but are still vital parts of the ecosystem that need to be left in place to conserve soil and water. These residues cycle soil nutrients, enhance the efficiency of fertilizer and irrigation, and feed soil bacteria and fungi essential to plant growth. Whatever fraction of biomass is removed from an ecosystem or farmer's field instead of being left to compost and recycle is a loss that must eventually be replaced or the soil will

be depleted. The thermodynamic checkbooks of energy and mass must be balanced.

The second fact is that, in a world of globalized economies, rich nations are not limited to their own territory. The high expense and environmental protection of land in the United States and developed nations leads energy farmers to look for cheaper land in less developed countries.[124] The United States and European nations are primarily pursuing offshore land indirectly through joint ventures, such as Blue Sugars' joint venture with Petrobras where Brazilian sugarcane bagasse feedstock was grown overseas and shipped to the United States for processing.[125] However, around the world today unscrupulous governments are confiscating land from villagers and burning forests wholesale to make way for lucrative biofuel plantations.[126] There is well-documented "green grabbing" of land in Latin America and Africa and Asia for cheap acreage and water rights needed for cash crops. A 2010 World Bank analysis revealed that wealthier countries including Saudi Arabia, South Korea, and China have already bought or leased more than 27 million acres of foreign land and water rights for remote cultivation of food, industrial, and biofuel crops. The chief locations for such appropriations are Sudan, Mozambique, Liberia, and Ethiopia, where governments are not protective of citizen land rights and more than 12 million persons are living hand-to-mouth on aid from the UN World Food Program.[127] This negative impact on rural native people is not likely to change as almost half of the world's potentially available arable land not already in food production is situated in only seven countries: Angola, Argentina, Bolivia, Brazil, Colombia, Democratic Republic of Congo and the Sudan.[128] The truth is that, even at today's small scale of production, biofuels' huge appetite for land already puts wealthy nations in significant and direct competition with global food production and the interests of the hungry. Food must and will eventually win this competition because there is not enough suitable land for both.[129]

Biofuels' huge appetite for land already puts the wealthiest nations in global competition with food production for the hungriest.

Section 11: Biofuels versus the Environment

Despite claims of reduced GHG and pollution emissions for biofuels, the reverse is now becoming apparent. Biofuels have roughly the same tailpipe or flue gas emissions as conventional fuels, but until recently they automatically earned "green" and "reduced emissions" badges through simplistic accounting tricks that assumed all their carbon was recycled from the atmosphere and also largely ignored the pollutants.[130] New more thorough studies that consider the full fuel creation and combustion lifecycles (as in Figures 3 and 4 above) are now showing cultivated liquid biofuels to be more damaging to the environment and causing the release of more CO_2 and other greenhouse gases and pollutants per unit of energy delivered than fossil fuels.[131]

11.1. Air and Water Pollution

Biofuels can be more threatening to the environment in some respects, and nowhere has this been more conspicuously ignored than with ethanol. The overall environmental impact and social costs of adding ethanol to gasoline as an oxygenate have been shown to be negative.[132] The only reason for oxygenating fuel is to reduce carbon monoxide emissions, yet ethanol does nothing to improve the carbon monoxide emissions of any US car built since 1993.[133] Like the MTBE oxygenate additive it replaced,[134] ethanol threatens water quality and increases the environmental hazard of spills because ethanol-blended gasoline is more water-soluble and leaches through the soil faster than straight gasoline. The EPA was presented with evidence in 1999 that ethanol may extend gasoline soil and groundwater pollution plumes 25-40% and inhibit natural gasoline biodegradation in the soil, but as yet the agency has established no national monitoring for environmental ethanol contamination as it did for MTBE.[135] Ethanol blending also makes open water contamination more difficult to clean up because more of the spilled fuel mixes with the water instead of floating on the surface and evaporating.[136] Ethanol unquestioningly reduces the fuel economy of every gasoline vehicle in direct proportion to its blending ratio,[137] increases emissions of some smog precursors, and requires a standing waiver from the EPA for their own air quality standards.[138] A blue ribbon panel of experts commissioned by the EPA in 1999 recommended discontinuing the use of all oxygenates in gasoline.[139]

11.2. Climate and CO_2

The most important change in the new lifecycle studies is the proper accounting of land use change driven by biofuel cultivation such as converting

forests to energy crop fields by burning. This widespread practice has been accelerated around the world by biofuels agriculture, and is releasing centuries of carbon sequestered in forest biomass back into the atmosphere from these natural carbon sinks. Such burning strikes a double blow because it also destroys a dense living biome with a huge perpetual appetite for CO_2. It is now calculated that large-scale conversion of virgin land to biofuel production has already released and continues to release so much CO_2 into the atmosphere that it may be centuries before this surge can be offset by the recycled carbon in the resulting biofuels, if at all. The continued burning of millions of acres of forest and peat lands to make room for oil palms has made Indonesia the world's third highest producer of CO_2 after the United States and China.[140] The additional global warming effects of land cultivation for biofuels are addressed in the nitrogen discussion below.

The principal efforts for halting global warming are currently directed at reducing CO_2 emissions and sequestering CO_2 out of the atmosphere. While developed nations with post-industrial economies are making some progress in CO_2 emission reductions by switching to lower carbon fuels, improving energy efficiencies, and shifting toward less energy-intensive service-oriented economies, these are dwarfed by increased releases from developing countries such as China, India and Indonesia.[141] The overall mass of humanity is still inexorably increasing its energy consumption as electricity and industry and modern amenities spread to the underdeveloped world, and global CO_2 emissions are rising 2-3% per year. There is no realistic prospect, short of decimating the human population, of reducing the 35 gigatons of CO_2 produced by civilization each year.[142] Just halting the annual increase would require converting 2-3% of global electrical power capacity to zero-emission plants each year without releasing any CO_2 in their construction.[143] That equates to 300-450 GW of power generation capacity, which is approximately half of US total capacity, and is tantamount to magically commissioning one new nuclear power plant every day of the year for decades to come.

While man-made carbon capture is still in its infancy, it is clear that there are finite limits and environmental risks to underground and deep-ocean storage. The only truly sustainable approach for the very long term (centuries) is to capture CO_2 the way nature has since the dawn of life, in the green biomass of plants and algae. Very counterproductive to that goal is large-scale burning of plants as fuel. The challenge of mitigating global warming is to increase the green carbon-inhaling biosphere to balance man's carbon dioxide-exhaling civilization. Maintaining living orchards and no-till grain fields with perennial biomass is a better approach for GHG emissions and for solving the challenges of the looming food crisis than converting vast tracts of land to biofuel commodity crops and harvesting even the crop residues normally left to preserve nutrients in the soil. One key pillar of a sound global warming mitigation strategy should be growing huge new volumes of biomass *and not burning them*.

One key pillar of a sound global warming mitigation strategy should be growing huge new volumes of biomass *and not burning them*.

11.3. The Nitrogen Problem

Nitrogen is on a path to becoming even more regulated than CO_2 because of the ecological damage it can cause. Nitrogen from fertilizer runoff is implicated in acid rain, in the nitrate poisoning (eutrophication) of one-third of US streams and two-fifths of US lakes, and in human disease.[144] Increased agriculture for biofuels has multiplied this challenge. Nitrous oxide (N_2O) is a gas released by ammonia-based fertilizer production and use. One N_2O molecule has 298 times the global warming potential of one molecule of CO_2.[145] N_2O currently contributes 8.4% of global warming radiative forcing, and its share is growing.[146] It is now also the top ozone-depleting compound being released into the atmosphere.[147] Between 1% and 5% of the nitrogen in ammonia fertilizer applied to cultivated crops escapes to the atmosphere as N_2O.[148] A host of new studies that consider both land use change and nitrogen effects conclude it is better for the climate and the environment to stick with conventional fuels than to put new land into cultivation for biofuels.[149] Section 526 of the *Energy Independence and Security Act of 2007* (EISA) specifies that the lifecycle GHG emissions of any alternative or synthetic fuel purchased by the US government must be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources.[150] In light of recent research, and in the interest of curbing global warming, the US Government should reexamine all Section 526 certifications so far given for biofuels and blends. Any that do not consider the full lifecycles including land use change, that neglect N_2O or any other GHG emissions, or that do not properly compare opportunity cost with conventional fuels should be invalidated.

Section 12: The Competition of Fuel and Food

In 2008, world grain market prices tripled, mirroring and surpassing the spike in global oil prices, and proving the linkage between food Calories and energy calories in the modern world. Grain prices to the poorest consumers increased as much as 50%, driving 8% more of Africa's population toward hunger and raising the world's undernourished population to approximately 850 million.[151] Today's market prices are still double what they were in 2007. Various studies of the 2008 food price spike surveyed by the World Bank have attributed as much as 70% of the increase in corn prices and 100% of the increase in sugar prices to global diversion of food to biofuels.[152] A union of the world's preeminent food and assistance agencies including the World Food Program and the Food and Agriculture Organization of the United Nations has formally called for all G20 nations to drop their biofuels subsidies and mandates because of the impact they are having on driving up food prices around the world.[153] It is a myth to think that non-food biofuel crops do not compete with food. Labels such as "Gen2" or "Advanced" can only serve as Orwellian attempts to hide the truth and assuage investor consciences. That fact is that every cultivated crop—food or non-food—competes with every other cultivated crop for finite resources including water, land, agrichemicals, farm equipment, transportation, financing, etc. Putting more demand on these resources raises prices for everyone. Biofuels are becoming a huge threat to global food security, and thereby to global stability—a fact that should shape any military or political energy strategy. Many analysts now looking at the "Arab Spring" phenomenon recognize that, underlying the very real political aspirations of movements such as the revolution in Tunisia, there was outrage at skyrocketing food prices. What first began as riots in Egypt due to the government no longer being able to afford to subsidize the price of bread became a hot-blooded revolt and *coup*.

Every cultivated crop competes with every other cultivated crop for finite resources including water, land, agrichemicals, farm equipment, and financing.

12.1. The Looming Global Food Crisis

As the global population sprints toward 9 billion by 2050, there are 140,000 more mouths to feed every day. Food grain consumption is growing at 40 million tons per year.[154] Yet, because of enormous market-distorting subsidies, the United States today produces more corn for ethanol than for food or cattle feed.[155] For decades past, America had surplus food crop capacity and used it to rescue other nations from famine. In 1965 President Lyndon Johnson's administration shipped

one-fifth of the US wheat crop to India during a devastating drought.[156] With slack land now being consumed by biofuels production, a drought such as the one that destroyed 40% of Russia's grain crop in 2010 would be devastating to national security—particularly because both food and fuel would be simultaneously affected. The negative consequences of biofuels upon food crop production have been understood by the US government since a blue-ribbon panel of scientists appointed by the newly formed DoE rejected gasohol for this and other sound reasons in 1980.[157] Twenty-five years later in 2005, politics trumped science with the imposition of US ethanol blending mandates and corn ethanol subsidies that even Al Gore now regrets—and the world is reaping what we have sown.[158] If our greater interest is truly global peace and security, US farmers should be out of the fuel business, and instead looking to increase food production to fill commodity and direct export orders with famine-wary nations in the overstressed global food market.

12.2. The Mineral Problem

Potash and phosphate are critical plant macro-nutrient minerals which must be provided in large quantities for both food and biofuel cultivation. The United States currently imports 85% of its potash supply.[159] In 2011 the global price of potash doubled, sending fertilizer prices skyrocketing.[160] In 2010 America imported 13% of its phosphate, and 90% of this came from Morocco, an Islamic kingdom of the North African Maghreb region that is a growing stronghold of Al Qaeda. In 2011, phosphate prices jumped $60 per ton. Replacing US transportation fuel with algae biodiesel would require about 88 million more tons of phosphate rock to be mined a year[161] compared to current US production of 28.4 million tons and total global production of 191 million tons.[162] While there is a loud chorus of pundits preaching doom about the price volatility of oil and US dependence upon unstable Persian Gulf nations (source of 13% of US crude in 2011), few are those who recognize how susceptible US agriculture is to foreign economic influences. Basing our transportation energy supply on agriculture via biofuels only exacerbates this risk. It is critically important for energy strategists and policy makers to realize that exchanging a fuel dependent on foreign crude oil imports for a fuel dependent on foreign potash and phosphate imports does not improve national security. In fact, it puts both food and fuel in jeopardy of a single embargo.

Exchanging a fuel dependent upon foreign oil imports for a fuel dependent upon foreign mineral imports does not improve national security.

12.3. The Water Problem

The final knife in the chest for biofuels is their water demand. "Water footprint" is the term for how much fresh water is consumed or rendered unusable by a particular activity. This can happen by evaporation, by removal to inaccessible

parts of the ecosystem, and by contamination with chemicals such as industrial discharges or crop fertilizer runoff. Water use also represents a dimension of competition with food agriculture, but it is even more urgent and fundamental in its own right. While "peak oil" continues to be elusive (global petroleum production and proved reserves both set new record highs in 2011,[163]), "peak water" has already arrived for much of the world. One third of all countries are today considered "water poor." Two of every five people do not have enough water for basic sanitation and nearly one in five do not have enough to drink.[164] Many scientists and economists today observe falling water tables and depleting aquifers due to over-pumping (including the massive Central Valley and High Plains aquifers in the United States) and predict this will expand to a global water crisis by 2030.[165]

Much of the Middle East and a growing number of other nations including China, Japan, Australia and Spain are now dependent upon desalination of seawater for a significant fraction of their fresh water needs.[166] To put this dependence in perspective, consider that the USS Carl Vinson, a Nimitz class aircraft carrier, can desalinate 400,000 gallons of water a day with its nuclear reactors, and recently used that capacity to assist Haiti with fresh water after its devastating earthquake.[167] The current desalination demand of the world exceeds 78 million cubic meters per day with 11% annual growth.[168] That equates to 51,500 aircraft carriers worth of desalination capacity with 5,600 more being built each year. Saudi Arabia in 2008 quietly abandoned a 40-year program to become self-sufficient in food production via huge state-of-the-art desert farms and greenhouses. The reason was the decreasing level of their "fossil water" aquifers and the growing expense of water desalination. Saudi Arabia's ground water production peaked in 1992, and today the country relies on desalination for 70% of its household water.[169] There is a growing direct economic convertibility in the world between liters of fuel and liters of water. Saudi Arabia is now willing to spend one liter of ethanol equivalent energy in crude oil to desalinate 200-300 liters of water in their massive Shoaiba facility.[170] How do those economics mesh with biofuels?

12.4. Water and Biofuels Don't Mix

Conventional gasoline has a water footprint of 2.3 to 4.4 liters of water per liter of ethanol equivalent energy (L/L) including water injected into the ground for enhanced oil recovery and water used in refining.[171] In contrast, global averages for biofuels range from sugar beet ethanol (1,388 L/L) to corn ethanol (2,570 L/L) to soy biodiesel (13,676 L/L) to rapeseed biodiesel (14,201 L/L) to jatropha biodiesel (19,924 L/L).[172] Current state of the art for installed seawater desalination plants ranges from 126 to 970 liters of water per liter of ethanol equivalent energy.[173] So, under absolute best case circumstances, sugar beet feedstock cannot produce enough ethanol fuel energy to desalinate enough water to grow a replacement crop, let alone provide leftover ethanol as fuel. Biofuels' huge dependence upon water means they are not truly a renewable fuel in any location where water is being depleted. *Not one biofuel crop is renewable in desalinated*

seawater. Under the President's recently published update to *Executive Order 13603* that specifies responsibilities under the *Defense Production Act* of 1950, the Secretary of Defense is now responsible for the US water supply.[174] That should cause reflection regarding DoD's promotion of biofuels. When Saudi Arabia and a third of the world are willing to spend a liter of fuel for less than 1,000 liters of water, how long can others get away with spending 10,000 liters of water or more for one liter of biofuel?

Biofuels are not renewable in any location where water resources are being depleted.

12.5. The Advent of the Global Water Market

The Chairman of Nestle Foods is one among a growing host who believe that ecological and population stresses on water will only be balanced by sound water management when water becomes a market commodity instead of a free utility.[175] According to Citigroup's chief economist, water will become "the single most important physical commodity based asset class, dwarfing oil, copper, agricultural commodities and precious metals."[176] At some point, governments will no longer be able to afford to subsidize water, just like many have had to abandon subsidizing wheat in the past two years, and will have to pass the costs on to their industries and populations. If they have not already succumbed to other factors, the establishment of a regional or global water market will be the death knell for biofuels. This is another eventuality with dramatic global implications that energy strategists should be anticipating.

Section 13: Can a Technology Breakthrough Save Biofuels?

Ultimately biofuels are limited by the sun. If they rely exclusively on the sun's energy and organic soil nutrients to make biomass without adding fossil fuel energy, the EROI can be high enough, but the power density will be far too low even with maximum theoretical photosynthesis performance. If yield is boosted with fossil fuel energy, fossil fuel use increases, biofuel EROI plummets and drags overall EROI with it, power density is still too low, and civilization ends up even more starved for power. The way out of this dilemma is to have a plentiful supply of hydrogen from a non-fossil fuel source, and the only prospect for doing this in sufficient quantity is to electrolyze hydrogen from water using nuclear power. However, if we had such a surplus of nuclear power electricity and hydrogen, we would use these directly for energy and fuel and not mess around with the inefficient middleman of biomass. This litany is the inescapable Catch-22 of biofuels.

Converting natural gas hydrocarbons into ammonia fertilizer and then into the carbohydrates of plant biomass is a sequence of transformations that irreversibly consumes significant usable energy in each step. That loss of energy can be justified if the crop being grown is food, and is of greater need than the energy used to grow it. However, completing the circle by converting that plant's carbohydrate biomass back into hydrocarbons for fuel makes the whole process a futile analog of the perpetual motion machine. Improvements in technology can reduce the percentage of energy lost in each conversion, but cannot eliminate it. Any wood, grass, peat, bagasse, coal, natural gas, or oil will deliver much more benefit to civilization if used directly and efficiently as fuel by a consumer whose needs are compatible with its limitations, rather than by using its energy to make biofuels. As long as the preponderance of ammonia and free hydrogen and organic compounds used in agriculture are derived from petroleum and natural gas, cultivating biofuels will defy all logic. They can never be cheaper than fossil fuels while fossil fuels comprise the bulk of the energy invested to make them.

Converting fossil fuel hydrocarbons into plant carbohydrates and then back into hydrocarbon fuels is a futile attempt at perpetual motion in chemistry.

Section 14: Conclusions and Recommendations

Imagine if the US military developed a weapon that could threaten millions around the world with hunger, accelerate global warming, incite widespread instability and revolution, provide our competitors and enemies with cheaper energy, and reduce America's economy to a permanent state of recession. What would be the sense and the morality of employing such a weapon? We are already building that weapon—it is our biofuels program. We need to quit the moonshine and face the sober facts. The DoD should pivot away from biofuels in its own energy strategy and the federal government should recraft its overall national energy strategy to be compatible with physics and biology and economics for the sake of national and global security. This revised strategy must acknowledge that:

1. The threshold test for any candidate for primary energy source or fuel is demonstrating the ability to bootstrap itself up in scale and energy productivity without outside assistance. This is equivalent to having an EROI greater than 1:1. The successful candidate will eventually have to do far better than this: it must surpass 6:1 to be minimally useful to modern civilization and match or exceed the 12:1 US average EROI to be commercially competitive. A true 21st century fuel must deliver enough energy profit to build up its own production and distribution infrastructure just as coal and oil did in the previous two centuries. Such a test quickly reveals that the quality of energy measured in such things as EROI, energy density, power density, and *dispatchability* (controllability of energy delivery location, timing, and rate)[177] matter just as much as total power output. Until this level of performance is achieved, the energy candidate is a research and development experiment that cannot survive without subsidy. Conversely, any energy candidate that is receiving a net subsidy is by definition not an energy source. The US government should not push to commercialize any energy candidate until it has demonstrated lifecycle performance at competitive EROI without subsidy.

2. Biomass is critically limited by the sun and biology to insufficient power density and energy density to be a viable national primary energy source or transportation fuel feedstock. Unfertilized biomass from unmanaged land (e.g., firewood) may offer some benefit to niche consumers who can abide its limitations, but it should be consumed as-is, without wasteful attempts at transformation to a liquid. Regardless of form, it simply cannot support the industrial, commercial, and transportation sectors of modern economies.

3. The best EROIs of today's cultivated liquid biofuels fall between those of agrarian Rome and the Stone Age. They would be even lower if not for stealing fossil fuel energy throughout their lifecycle. None have any prospect

of simultaneously attaining the 6:1 threshold EROI necessary to marginally support a modern civilization, let alone 12:1 to match the current US average, while also achieving the power density and energy density necessary to supplant a significant fraction of the national transportation fuel supply.

4. Current US biofuels policy is increasing ecological damage and GHG emissions due to destructive global land use change, harmful agrichemical side-effects, and the accelerated consumption of fossil fuel. This is the exact opposite of "clean and green." The US military and federal government need to rationally and authoritatively define "renewable," "sustainable," and "green," and enforce empirical standards for meeting these criteria based upon rigorous lifecycle and opportunity cost analyses.

5. Recent research indicates that cultivated liquid biofuels are not renewable in water, are not green in ecological footprint, and are not sustainable in energy balance. EISA Section 526 Certifications performed without the benefit of this research and without full consideration of land use change and all GHG emissions should be invalidated and redone.[178]

6. The best case power density predicted to ever be achievable for any biofuel is already attained by today's PV solar panels. The US government should cease subsidizing biofuels and instead offer prizes for milestones in improved PV solar panel performance.

7. Biomass is an inefficient middleman between solar energy and fuel. A better approach is to bypass the creation of biomass completely and directly synthesize liquid fuel from sunlight. The US government should cease funding biofuel research and instead offer prizes for milestones in direct fuel photosynthesis.[179]

8. Refined petroleum is currently unbeatable as transportation fuel, and it is to civilization's net loss if it is used to process biomass into inferior fuels. Doing so represents a huge opportunity cost and accelerates the arrival of any day of future petroleum scarcity.

9. The diversion of any fossil fuel energy to boost biofuel yields (in the form of synthesized ammonia or sugar nutrients, pesticide or herbicide, farm equipment fuel, transportation fuel, processing plant energy, distillation energy, enzyme and organic chemistry feedstock, or hydrotreatment hydrogen) is wasteful of energy, undermines the very purpose of alternative fuels to replace fossil fuels, and reduces the overall EROI of the nation. The federal government should prohibit the use of fossil fuel-derived fertilizers and agrichemicals on energy crops.

10. Use of fossil fuel energy to accelerate food crop growth can be justified as a necessary trade, but the dependencies of agriculture upon external energy sources need to be explicitly quantified to improve the efficient operation of

both the food and energy realms. Those in the agricultural arts and sciences should begin to account for energetic hydrogen from ammonia, urea, and sugar as carefully as they currently account for nitrogen, phosphorus, potassium, and carbon. Farmers who recognize the fertilizing power of hydrogen may shift toward fertilizers with greater hydrogen-to-nitrogen ratios and help ease the blights of nitrate runoff and eutrophication that result from over-application of nitrogen.[180]

11. Government energy policies that restrict domestic development of a nation's highest EROI energy sources and fuels such as hydropower, coal, natural gas, and petroleum are tantamount to caps on thermodynamic efficiency, economic health, and international competitiveness. Conversely, the nations that pursue the highest EROI energies will have the greatest potential to grow their economies and have every prospect of advantage over countries limited to lower EROI sources. The government should end subsidies and market-distorting policies that encourage low-EROI energy sources over high-EROI sources.

12. Global air and long-haul transportation are currently very dependent upon liquid hydrocarbon energy, and it is unlikely that physically superior combustion fuels will be found. If the world runs out of fossil fuels without an alternative source for massive amounts of energetic hydrogen and carbon, civilization also immediately runs out of transportation fuel. To the extent that oil and gas are judged to be running out, the government should ensure there is excess electrical capacity from non-oil and gas power plants to electrolyze sufficient quantities of hydrogen from water for transportation fuel purposes.

13. Global food production is currently very dependent upon fossil fuel energy. If the world runs out of fossil fuels without an alternative source for massive amounts of energetic hydrogen, civilization also immediately runs out of both biofuels *and food*. To the extent that oil or gas are judged to be running out, the government should ensure there is excess electrical capacity from non-oil and gas power plants to electrolyze sufficient quantities of hydrogen from water for food agriculture purposes.

14. The best use of agricultural land and water is growing food for one's own country and a surplus to cover global shortages. This has been before and again can be a significant US contribution to international security and stability.

15. The technologies most in need of Manhattan Project attention by our global security strategists and national scientific laboratories at this very minute are sustainable water production and food agriculture to support the 9 billion people of 2050. The US government should cease funding biorefinery construction and instead offer prizes for milestones in food production and water desalination efficiencies.

16. CO_2 is not the only GHG. Agriculture is the leading producer of N_2O and a major producer of CH_4, which together comprise more than 26% of current total atmospheric GHG effects.[181] The US government should levy any caps or taxes equitably across all greenhouse gases in proportion to their global warming potentials. Any per-ton penalties imposed on CO_2 should be levied against CH_4 at 69 times the rate, and against N_2O at 298 times the rate to reflect their relative per-ton global warming potentials.[182]

17. The price of oil, like that of any other global free market commodity, is volatile and subject to war, politics, and speculation. However, global markets, on average, deliver better prices than regional or local markets. Biofuels are not only subject to energy market forces, but are also subject to agricultural market forces and the vagaries of the weather. Biofuel prices are already proving to track with oil prices and to match their volatility, and it is likely to get worse once subsidies and guaranteed markets are abolished. Regardless of this, it is logically indefensible to buy a $30.00 per gallon fuel over worries about the price volatility of a $3.00 per gallon fuel.

18. Military dependence upon petroleum is less of a national security risk than dependence upon biofuels. Petroleum is produced in more than 80 countries, global proved reserves are over 1.6 trillion barrels and growing, and a century and a half of capital investment has made petroleum fuels available in every major port and airfield on Earth. In contrast, liquid biofuels derive 80% or more of their energy content from fossil fuel and go away if fossil fuels go away; are subject to interruption by weather events such as drought, freeze, and flood; have zero proved reserves and must be made season-by-season; are encumbered with the price volatility of both the energy and agricultural markets; are neither globally standardized nor globally available; and are money sinks for a federal government $16 trillion in debt.

Modern civilization has progressed to the point where its underlying technology often operates according to counterintuitive laws and at scales of size, complexity, and interconnectedness that surpass common human experience. Sound decisions cannot be made based solely upon popular opinion, personal opinion, orthodox worldviews, or even common sense. Wise leaders must have "uncommon sense" founded upon a broad and deep education, and keen insight achieved through thorough study of the science and the empirical evidence of the issue at hand. National energy strategy is nothing less than national survival strategy. Those who would craft such strategy or advise policy-makers need to be well-grounded in chemistry, thermodynamics, biology, and economics, so they might discern the difference between promising avenues of research and perpetual motion schemes that defy physical laws and waste our nation's time and treasure. Trying to biofuel our way to energy independence is like medieval physicians trying to bleed their patients back to health. It is time to stop the bleeding.

Notes

[1] Öko-Institut (Freiburg im Breisgau, Germany), and IEA Bioenergy Programme. The Bioenergy and Water Nexus. [Nairobi, Kenya]: United Nations Environmental Programme, 2011.

[2] See 1. James S. Kus, "The Chicama-Moche Canal: Failure or Success? An Alternative Explanation for an Incomplete Canal," *American Antiquity* 49, no. 2 (April 1, 1984): 408-415; and 2. Charles Mann, *1491: The Americas Before Columbus* (London: Granta, 2006). It is debated by archaeologists how much of the Chimu canal failure is attributable to faulty topographical surveys, faulty engineering, or shifting fault lines from a landscape that was geologically active in the past.

[3] Sherrard and Kressman. "Review of Processes in the United States Prior to World War II." Industrial & Engineering Chemistry 37, no. 1 (January 1, 1945): 5–8. http://pubs.acs.org/cgi-bin/doilookup/?10.1021/ie50421a003.

[4] "The Early Days of Coal Research." Department of Energy, November 13, 2012. http://fossil.energy.gov/aboutus/history/syntheticfuels_history.html.

[5] See 1. "Historical Price Viewer." Energy Information Administration. http://www.eia.gov/forecasts/steo/realprices/; and 2. Pimentel et al. *Report of the Energy Research Advisory Board on Gasohol*. Gasohol Study Group, April 29, 1980.

[6] Sheehan et al. *A Look Back at the US Department of Energy's Aquatic Species Program: Biodiesel from Algae*. Vol. 328. National Renewable Energy Laboratory, 1998.

[7] See 1. Bartis et al. *Alternative Fuels for Military Applications*. RAND National Defense Research Institute, 2011. http://www.rand.org/pubs/monographs/MG969.html; and 2. Dina Fine Maron. "Biofuels of No Benefit to Military -- RAND." New York Times, January 25, 2011. http://www.nytimes.com/cwire/2011/01/25/25climatewire-biofuels-of-no-benefit-to-military-rand-11643.html.

[8] See 1. Bartis et al. Project Air Force (U.S.), and RAND Corporation. *Promoting International Energy Security*. Santa Monica, CA: RAND, 2012. http://www.rand.org/pubs/technical_reports/TR1144z1.html; and 2. National Academy of Sciences - National Research Council. *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*. Washington, D.C.: The National Academies Press, 2011. http://www.nap.edu/catalog.php?record_id=13105.

[9] *Bioenergy - Chances and Limits*. Nationale Akademie der Wissenschaften - Leopoldina, 2012. http://www.leopoldina.org/en/publications/detailview/?publication[publication]=433.

[10] National Research Council - Committee on the Sustainable Development of Algal Biofuels. *Sustainable Development of Algal Biofuels in the United States*. Washington, D.C.: The National Academies Press, October 2012. http://www.nap.edu/catalog.php?record_id=13437.

[11] 10 USC § 2924 - Definitions. December 31, 2011. Contains definitions of "energy security," operational energy," and "renewable energy sources," among others, as specified in the National Defense Authorization Act of 2012. http://www.law.cornell.edu/uscode/text/10/2924?quicktabs_8=1#quicktabs-8.

[12] "How Much Petroleum Does the United States Import and from Where?" *Energy Information Administration*, July 16, 2012. http://www.eia.gov/tools/faqs/faq.cfm?id=727&t=6.

[13] A liter of gasoline contains 116 grams of hydrogen compared to 71 grams per liter in pure liquid hydrogen.

[14] Once ammonia becomes available in the soil or plant roots it can react inorganically with water and oxygen and decomposes into hydrogen gas, hydrogen ions, and nitrate ions in a process known as "nitrification." Partial oxidation of ammonia produces the GHG nitrous oxide (N_2O) and hydrogen gas: $2NH_3 + O_2 \text{ —> } N_2O + H_2O + 2H_2$. Full decomposition of ammonia in water solution with oxygen produces nitric acid and water completing nitrification: $NH_3 + H_2O + 2O_2 \text{ —> } 2H^+ + NO_3^- + OH^- + H_2O$. Nitrification can also be accomplished through the action of *nitrosomas* microbes that break down ammonia into nitrite (NO_2^-) to release metabolic energy, and *nitrobacter* microbes that break down nitrite into nitrate (NO_3^-) for metabolic energy. Organisms that have the hydrogenase uptake enzyme (HUP+) can capture and oxidize H_2 into $2H^+ + 2e^-$ and harvest that energy. This includes the *rhizobium*, *azotobacter*, and *cyanobacteria* microbes that live in roots and soil and fix nitrogen. See 1. Z. Dong and D.B. Layzell. "H_2 Oxidation, O_2 Uptake and CO_2 Fixation in Hydrogen Treated Soils." *Plant and Soil* 229, no. 1 (2001): 1–12. http://www.springerlink.com/content/qp73k5770103075r/abstract/. Thus the hydrogen from soil ammonia is fueling the symbiotic soil- plant biome even before any nitrate nitrogen is taken up by the plant. See 2. Stein et al. "Microbial Activity and Bacterial Composition of H_2-treated Soils with Net CO_2 Fixation." *Soil Biology and Biochemistry* 37, no. 10 (October 2005): 1938–1945; 3. Ducat et al. "Rewiring Hydrogenase-dependent Redox Circuits in Cyanobacteria." *Proceedings of the National Academy of Sciences* 108, no. 10 (March 8, 2011): 3941–3946. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3053959/; and 4. Simpson and Burris. "A Nitrogen Pressure of 50 Atmospheres Does Not Prevent

Evolution of Hydrogen by Nitrogenase." *Science* 224, no. 4653 (June 8, 1984): 1095–1097. http://www.sciencemag.org/cgi/doi/10.1126/science.6585956.

[15] These molecular fractions are based on ultimate analysis mass fractions of 32 species of cultivated biomass which yielded averages of of 47.9% carbon, 5.7% hydrogen, 41.1% oxygen, 0.5% nitrogen, and 4.8% other elements.

[16] These processes include the ATP-ADP, NAD-NADH, and FAD-$FADH_2$ reactions that power photosynthesis and cellular metabolism.

[17] There are several competing formulae for approximating the combustion higher heating values (HHV) of biomass: Boie, Dulong, Mason and Gandhi, Gaur and Reed, Channiwala, etc. All agree that hydrogen and carbon carry the preponderance of the potential combustion energy and that the presence of nitrogen and oxygen in the fuel actually decrease the energy density. See 1. Gaur and Reed. *An Atlas of Thermal Data For Biomass and Other Fuels*. National Renewable Energy Laboratory, June 1995. http://www.nrel.gov/docs/legosti/old/7965.pdf. Coefficients for calculating HHV in MJ/kg by applying the ultimate analysis mass fraction of each element = (+1.1783 x H) + (+0.3491 x C) + (+0.1005 x S) + (-0.0151 x N) + (-0.1034 x O) + (-0.0211 x (K + other minerals)) per S. A. Channiwala, "On Biomass Gasification Process and Technology Development - Some Analytical and Experimental Investigations." Ph.D. thesis, IIT Bombay, Mumbai, 1992.

[18] Reforming CO_2 and H_2O into simple sugar follows the stoichiometry: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6$ (glucose), with a change in enthalpy (ΔH) of $\approx$ 2.8 MJ/mol. ΔH for methane combustion of the same molecular mass ($3CH_4 + 6O_2 \rightarrow 3CO_2 + 6H_2O$) is $\approx$ -2.6 MJ/mol. Fossil fuel, after being geologically processed from plant or animal carbohydrates into hydrocarbons, still retains more than 90% of the photosynthesis energy of the original ancient biomass, and the only cost to civilization to get this concentrated energy is extracting it form the ground and refining it. The huge amount of energy already input by the earth for free to transform solid biomass into liquid fuel is why biofuels have such a hard time competing with fossil fuels. See "Photosynthesis." GenChem Textbook, n.d. http://chemed.chem.wisc.edu/chempaths/GenChem-Textbook/Photosynthesis-979.html.

[19] The widely accepted value for "biomass accumulation efficiency," which is the fraction of total incident solar energy converted into biomass by photosynthesis, is 0.1% for most terrestrial plants. Plants actually make use of a much higher fraction of the sun's energy, but most of it goes into overhead costs such as evaporating water from the leaves to perform the work of drawing up nutrients from the ground against the force of gravity. Efficiencies as high as 4% under

special circumstances have been reported, and it may be possible to boost this to 8% in laboratory conditions with human reengineering of the enzymes and mechanics. However, the highest efficiencies are achieved at very low light fluxes. Photosynthesis is saturated in capacity between 20% and 50% of maximum solar irradiance, and plants suffer radiation damage at these higher levels. Gains in net biomass accumulation remain elusive. See 1. Zhu et al. "What Is the Maximum Efficiency with Which Photosynthesis Can Convert Solar Energy into Biomass?" *Current Opinion in Biotechnology* 19, no. 2 (April 2008): 153–159. http://linkinghub.elsevier.com/retrieve/pii/S0958166908000165; 2. Blankenship et al., "Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement." *Science* 332, no. 6031 (May 12, 2011): 805–809; 3. Michel. "The Nonsense of Biofuels." *Angewandte Chemie International Edition* 51, no. 11 (March 12, 2012): 2516–2518. http://doi.wiley.com/10.1002/anie.201200218; and 4. "Renewable Biological Systems for Alternative Sustainable Energy Production: Chapter 1 - Biological Energy Production." *Food and Agriculture Organization of the United Nations*, September 7, 2012. http://www.fao.org/docrep/w7241e/w7241e05.htm#1.2.1. For aquatic photosynthesis, see 5. Weyer et al. "Theoretical Maximum Algal Oil Production." *BioEnergy Research* 3, no. 2 (October 8, 2009): 204–213. http://www.springerlink.com/index/10.1007/s12155-009-9046-x.

[20] The National Renewable Energy Laboratory reports that solar radiation across the spectrum delivers energy to the cloudless southwestern US desert at a rate of 7.25 kWh/m^2-day = 302 W/m^2. At the observed biomass accumulation efficiency of 0.1%, this equates to 0.3 W/m^2 put into plant biomass, of which only a fraction can be eventually recovered as liquid fuel. See 1. "Concentrating Solar Resource: Direct Normal - Annual". National Renewable Energy Laboratory, February 2009. http://www.nrel.gov/gis/images/map_csp_us_10km_annual_feb2009.jpg.

[21] Solar photo-voltaic (PV) AC power density of 6.0 W/m^2 is the current real-world best-case for large solar farm sites in optimal US locations. This value is based on empirical analysis of nearly five years of actual performance of the Nellis AFB solar power plant (Dec 2007 completion, $100M, 72,416 panels on 140 acres, 14MW_{pv} (13MW_{ac}) nameplate capacity, single-axis tracking array, 19% land coverage density, 24.5% capacity factor, producing 30 GWh/yr). See 1. "Nellis AFB Solar Power System". *U.S. Air Force*, accessed August 22, 2012. http://www.nellis.af.mil/shared/media/document/AFD-080117-043.pdf; and 2. "SunPower Monitor - Nellis Air Force Base." *Sunpower Performance Monitoring*, August 2012. http://commercial.sunpowermonitor.com/Commercial/kiosk.aspx?id=1dd14d57-7840-4b2d-af0a-0fe0fdd5c872.

[22] "Nitrogen-fixing" should really be known as "ammonia-fixing." Most agricultural literature completely bypasses any mention of hydrogen as a fertilizer component and instead focuses exclusively on nitrogen or "N." This dates from the days before widespread use of synthetic ammonia when nitrogen was exclusively applied in mineral salt form as sodium nitrate ($NaNO_3$) or potassium nitrate (KNO_3) without any of the hydrogen energy carriers of the ammonia-based forms. If soil is deficient in nitrogen, then adding this critical nutrient in mineral or ammoniacal form will improve crop health and yield. However, applying mineral nitrogen above the necessary nutrient level is less effective and can even be poisonous to plants. Only recently has hydrogen been explicitly recognized as a fertilizer in its own right. Crops respond with dramatically increased yields to energy supplied in any form of the ammonia molecule including anhydrous ammonia (NH_3), the ammonium ion (NH_4^+), and urea ($(NH_2)_2CO$). In each of these molecules, the hydrogen atoms are also energy carriers and greatly outnumber the nitrogen. Studies have also shown that fertilizing with pure hydrogen gas (H_2) without adding any nitrogen at all can greatly boost soil bacteria activity and plant biomass synthesis. See 1. Dong and Layzell. "H_2 Oxidation, O_2 Uptake and CO_2 Fixation in Hydrogen Treated Soils." *Plant and Soil* 229, no. 1 (2001): 1–12. http://www.springerlink.com/content/qp73k5770103075r/abstract/. Seventy-five percent of the beneficial effect of legumes on crop rotation is not explainable by nitrogen nutrition and is now believed to be due to residual hydrogen in the soil. See 2. Dean et al. "Soybean Nodule Hydrogen Metabolism Affects Soil Hydrogen Uptake and Growth of Rotation Crops." *Canadian Journal of Plant Science* 86, no. Special Issue (December 2006): 1355–1359. http://pubs.aic.ca/doi/abs/10.4141/P06-082; and 3. Dong et al. "Hydrogen Fertilization of Soils - Is This a Benefit of Legumes in Rotation?" *Plant, Cell and Environment* 26, no. 11 (November 2003): 1875–1879. http://doi.wiley.com/10.1046/j.1365-3040.2003.01103.x. Applying hydrogen-rich ammonia fertilizer to crops that are robust nitrogen fixers such as soy still results in substantial gains. See 4. Ferguson et al. "Fertilizer Recommendations for Soybean." University of Nebraska Institute of Agriculture and Natural Resources, August 2006. http://www.ianrpubs.unl.edu/live/g859/build/g859.pdf. Further evidence of hydrogen's efficacy in boosting biosynthesis is the observed preferential uptake of ammonium ($NH_4^{+)}$ versus nitrate (NO_3^-) by plants and phytoplankton. See 5. Jackson et al. "Roots, Nitrogen Transformations, and Ecosystem Services." *Annual Review of Plant Biology* 59, no. 1 (2008): 341–363. http://www.annualreviews.org/doi/abs/10.1146/annurev.arplant.59.032607.092932; and 6. Dortch, Quay. "The Interaction Between Ammonium and Nitrate Uptake in Phytoplankton." *Marine Ecology Progress Series* 61 (March 8, 1990): 183–201. http://www.int-res.com/articles/meps/61/m061p183.pdf.

[23] Symbiotic rhizobial root bacteria get sugar from the host plant and use some of that energy and hydrogen to create NH_3 and H_2 gas and release these to the plant and into the soil. Soil bacteria metabolize the soil ammonia and H_2 and use that energy to break down soil minerals and materials such as chitin and lignin in

humus into mineral nutrients and energetic reduced carbon usable by the plant. For various aspects of the energy relationship between plants, bacteria, and ammonia, see 1. Mylona et al. "Symbiotic Nitrogen Fixation." *The Plant Cell*, no. 7 (July 1995): 869–885. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC160880/; 2. Hayat et al. "Soil Beneficial Bacteria and Their Role in Plant Growth Promotion: a Review." *Annals of Microbiology* 60, no. 4 (August 28, 2010): 579–598. http://u-tokyo.academia.edu/IFTIKHARAHMED/Papers/293426/Soil_Beneficial_Bacteria_and_Their_Role_In_Plant_Growth_Promotion_a_Review; 3. Sanguinetti et al. "MMG: a Probabilistic Tool to Identify Submodules of Metabolic Pathways." *Bioinformatics* 24, no. 8 (February 21, 2008): 1078–1084. http://bioinformatics.oxfordjournals.org/cgi/doi/10.1093/bioinformatics/btn066; and 4. Matiru and Dakora. "Potential Use of Rhizobial Bacteria as Promoters of Plant Growth for Increased Yield in Landraces of African Cereal Crops." *African Journal of Biotechnology* 3, no. 1 (2004): 1–7. http://www.ajol.info/index.php/ajb/article/view/14908.

[24] Gibson et al. "Origin, History and Uses of Corn." *Iowa State University Department of Agronomy*, January 2002. http://www.agron.iastate.edu/courses/agron212/readings/corn_history.htm.

[25] Worrell et al. *Energy Use and Energy Intensity of the US Chemical Industry*. Lawrence Berkeley National Laboratory, April 2000.

[26] *Mineral Commodity Summaries 2012*. US Geological Survey, January 24, 2012. http://minerals.usgs.gov/minerals/pubs/mcs/.

[27] Hydrogen-free sodium-nitrate fertilizer ($NaNO_3$) comprised only 0.046% of commercial nitrogen fertilizer use in 2010 (13,000 of 28,000,000 tons). "Fertilizer Use and Price." USDA Economic Research Service, May 4, 2012. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx.

[28] Gibson et al.

[29] Blackmer et al. "Nitrogen Fertilizer Recommendations for Corn in Iowa". *Iowa State University*, May 1997. http://www.extension.iastate.edu/Publications/PM1714.pdf.

[30] Corn grain yield data from 1. "QuickStats Ad-hoc Query Tool." *USDA National Agricultural Statistics Service*, January 28, 2013. http://quickstats.nass.usda.gov/results/53B3BBDE-5AB4-3595-89FC-B691FF3F338E; Ammonia consumption data from 2. "Nitrogen (fixed) - Ammonia Statistics." US Geological Survey, November 10, 2011. http://minerals.usgs.gov/ds/2005/140/ds140-nitro.xls.

[31] Breeding and altered genetics have resulted in many crop improvements such as increased resistance to pests and disease, herbicide tolerance, drought and salt tolerance, freeze resistance, etc. But the principal effect of these alterations is to increase the fraction of planted crop that is ultimately harvested. The maximum yield is bounded by energy input, which is sunlight, reduced carbon, reduced hydrogen, and ammoniacal nitrogen compounds. Field research indicates that without artificial fertilizer, US crop yields would drop at least 50%. Stewart et al. "The Contribution of Commercial Fertilizer Nutrients to Food Production." *Agronomy Journal* 97, no. 1 (2005): 1. https://www.agronomy.org/publications/aj/abstracts/97/1/0001.

[32] Tadeusz W. Patzek, "A Probabilistic Analysis of the Switchgrass Ethanol Cycle," *Sustainability* 2, no. 10 (September 2010), 3158–3194, www.mdpi.com/2071-1050/2/10/3158/.

[33] A large-scale attempt to commercialize jatropha for biodiesel in Southern India produced yields 1/10th of those promised. The crop was a poor fit with the local ecological and socio-economic conditions, and 70% of plantations were uprooted or abandoned, having economically ruined participating farmers. See Slade et al. *Energy from Biomass: The Size of the Global Resource (2011)*. UK Energy Research Centre, 2011. http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2095.

[34] Higher volumetric energy density combustion materials include beryllium, aluminum, silicon, carbon, lithium borohydride ($LiBH_4$), hexamine ($C_6H_{12}N_4$), and high-density plastics synthesized from petroleum—all solids.

[35] See 1. *ORNL Ethanol Pipeline Corrosion Literature Study Final Report*. Oak Ridge National Laboratory, May 19, 2008. http://www.ornl.gov/sci/ees/itp/documents/ORNL%20Ethanol%20Pipeline%20Corrosion%20Literature%20Study%20Final%20Report.pdf; and 2. Bunting et al. *Fungible and Compatible Biofuels: Literature Search, Summary, and Recommendations*. Oak Ridge National Laboratory, September 30, 2010.

[36] Higher heating value (HHV) volumetric energy densities of various alternatives (MJ/liter): petroleum diesel (38.3), biodiesel (35.7), jet A-1/JP-8 (34.9), gasoline (34.7), isobutanol (28.9), cryogenic liquid natural gas (23.6), ethanol (23.5), fast pyrolysis bio-oil from wood (21.7), ammonia (12.7), cryogenic liquid hydrogen (10.1), lithium thionyl chloride battery (3.75), methanol fuel cell (1.38), lithium-ion battery (1.33). The lower the number, the proportionately longer the convoy.

[37] Hydrotreatment is most often used as a collective term for a set of processes necessary to refine or upgrade biofuels into true hydrocarbons that are "drop-in" compatible substitutes for conventional hydrocarbon applications. These processes include hydrogenation, deoxygenation, cracking, isomerization, fractionation, and adding additives as necessary to adjust energy density, cetane, octane, volatility, flammability, cold flow properties, lubricity, elastomeric seal compatibility, etc. See Munoz et al. *Production of Renewable Diesel Fuel*. University of Idaho: National Institute for Advanced Transportation Technology, June 2012. http://ntl.bts.gov/lib/46000/46200/46277/KLK766_N12-08.pdf.

[38] Other similar formulations of energy balance ratios include energy return on energy investment (EROEI), energy cost of energy (ECE), energy intensity ratio (EIR) and energy return on investment (ERI). EROI is the most common formulation in the literature, but there is some debate over what boundaries to apply to the formula. What is offered here is the simplest formulation of the concept.

[39] S. A. L. M. Kooijman, *Dynamic energy and mass budgets in biological systems* (Cambridge University Press, 2000).

[40] Timothy Garrett. "How Persistent Is Civilization Growth?" arXiv:1101.5635 (January 28, 2011). http://arxiv.org/abs/1101.5635.

[41] Timothy Garrett, "No way out? The double-bind in seeking global prosperity alongside mitigated climate change," *Earth System Dynamics* 3, no. 1 (January 5, 2012): 1-17.

[42] This author computed EROIs from data provided in Thomas Homer-Dixon, *The Upside of Down: catastrophe, creativity, and the renewal of civilization* (Washington: Island Press, 2006), and additional supporting material made available online at http://www.theupsideofdown.com/rome/colosseum/.

[43] Ibid. EROI for both humans and oxen as the ratio of maximum work output divided by food calorie input was calculated by this author from Homer-Dixon's online data as 0.175:1. EROI for Roman wheat as ratio of food calorie output divided by labor and seed grain inputs was 10.52:1. EROI for alfalfa was 26.99:1. Humans eating wheat yield a heavy labor EROI of 0.175 x 10.52 = 1.84:1. Oxen eating alfalfa yield a heavy labor EROI of 0.175 x 26.99 = 4.72:1. Teaming humans with oxen and applying various reductions for idle time and for those performing light work/skilled labor versus heavy labor according to Homer-Dixon's research gives the overall peak and sustained EROIs of 4.2:1 and 1.8:1 quoted.

[44] This tipping point is also correlated with greater than 10% GDP expenditures on energy. See C. W. King, "Energy intensity ratios as net energy measures of

United States energy production and expenditures," *Environmental Research Letters* 5, no. 4 (October 1, 2010): 044006.

[45] Hall et al., "What is the Minimum EROI that a Sustainable Society Must Have?," *Energies* 2, no. 1 (January 23, 2009): 25-47. The case considered in detail is liquid transportation fuel for modern civilization, which is exactly applicable

[46] Murphy et al., "Year in review—EROI or energy return on (energy) invested," *Annals of the New York Academy of Sciences* 1185, no. 1 (January 1, 2010): 102-118.

[47] X-axis energy contributions are EIA data for 2010 reported in 1. "Estimated U.S. Energy Use in 2010: ~98.0 Quads." Lawrence Livermore National Laboratory, 2011. https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2010/LLNLUSEnergy2010.png. Y-axis EROI values are depicted as ellipses to capture the range of values reported in different studies and for different sites. These values derived from this author's synthesis of published literature review including the following documents: 2. Department of Energy. "Fact Sheet: Energy Efficiency of Strategic Unconventional Resources.pdf." *Fossil Energy*, accessed Jan 29, 2012. http://fossil.energy.gov/programs/reserves/npr/Energy_Efficiency_Fact_Sheet.pdf; 3. Nate Hagens. "Proper Calculation of Brazilian Sugar Cane EROI." *The Oil Drum*, March 24, 2009. http://netenergy.theoildrum.com/node/5183#comment-486247; 4. Guilford et al. "A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production." *Sustainability* 3, no. 10 (October 14, 2011): 1866–1887. http://www.mdpi.com//2071-1050/3/10/1866/; 5. Charles A. S. Hall. "Wave & Geothermal." *The Oil Drum*, May 14, 2008. http://www.theoildrum.com/node/3949; 6. ———. "Why EROI Matters." *The Oil Drum*, April 1, 2008. http://www.theoildrum.com/node/3786; 7. ———. "Provisional Results." *The Oil Drum*, April 8, 2008. http://www.theoildrum.com/node/3810; 8. ———. "Unconventional Oil: Tar Sands and Shale Oil." *The Oil Drum*, April 15, 2008. http://www.theoildrum.com/node/3839; 9. ———. "Nuclear Power." *The Oil Drum*, April 22, 2008. http://www.theoildrum.com/node/3877; 10. ———. "Solar, Wind and Hydro." *The Oil Drum*, April 29, 2008. http://www.theoildrum.com/node/3910; 11. Hall et al. "What Is the Minimum EROI That a Sustainable Society Must Have?"; 12. Hall et al. "Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels." *Sustainability* 3, no. 12 (December 13, 2011): 2413–2432. http://www.mdpi.com/2071-1050/3/12/2413/htm; 13. Hill et al. "Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels." *Proceedings of the National Academy of Sciences* 103, no. 30 (2006): 11206; 14. C. W. King. "Energy Intensity Ratios as Net Energy Measures of United States Energy Production and Expenditures." *Environmental Research Letters* 5, no. 4 (October 1, 2010): 044006. http://iopscience.iop.org/1748-9326/5/4/044006; 15. King and Hall. "Relating Financial and Energy Return on Investment." *Sustainability* 3, no. 10 (October 11, 2011): 1810–1832. http://www.mdpi.com//2071-

1050/3/10/1810/; 16. David Murphy. "EROI Update: Alberta Tar Sands Toe-to-Heel Air Injection." *The Oil Drum*, March 18, 2009. http://netenergy.theoildrum.com/node/5183; 17. David Murphy. "The Energy Return on Investment Threshold." *The Oil Drum*, November 25, 2011. http://www.theoildrum.com/node/8625; 18. Murphy et al. "New Perspectives on the Energy Return on (energy) Investment (EROI) of Corn Ethanol." *Environment, Development and Sustainability* 13, no. 1 (July 11, 2010): 179–202. http://www.springerlink.com/index/10.1007/s10668-010-9255-7; 19. Murphy et al. "Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels." *Sustainability* 3, no. 10 (October 17, 2011): 1888–1907. http://www.mdpi.com/2071-1050/3/10/1888; 20. Tad W. Patzek. "A First-Law Thermodynamic Analysis of the Corn-Ethanol Cycle." *Natural Resources Research* 15, no. 4 (February 22, 2007): 255–270. http://www.springerlink.com/index/10.1007/s11053-007-9026-9; 21. Bruce Pile. "The Alternative Energy No One Is Thinking About." *Seeking Alpha*, accessed January 13, 2012. http://seekingalpha.com/instablog/152129-bruce-pile/7480-the-alternative-energy-no-one-is-thinking-about. 22. Pimentel and Patzek. "Ethanol Production: Energy and Economic Issues Related to U.S. and Brazilian Sugarcane." *Natural Resources Research* 16, no. 3 (August 21, 2007): 235–242. http://www.springerlink.com/index/10.1007/s11053-007-9049-2; 23. Shapouri et al. "Estimating the Net Energy Balance of Corn Ethanol." *Agricultural Economic Report* 721 (July 1995). http://content.imamu.edu.sa/Scholars/it/net/usda_shapouri.pdf.

[48] Corn ethanol EROI values in the literature cluster between 0.7:1 to 1.7:1 with a median value of 1.2:1. Many meta-studies comparing and contrasting multiple EROI approaches and papers have also been performed. This author judges the most thorough and authoritative individual study to be 1. Hill et al., "Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels," *Proceedings of the National Academy of Sciences* 103, no. 30 (2006): 11206. This study is one of several to promulgate a value of 1.25:1, and to find that any positive energy balance was entirely dependent upon giving energy credit for co-products. The most thorough and authoritative of the recent meta-studies surveying multiple individual corn ethanol life-cycle analyses was judged to be 2. Murphy et al. "New Perspectives on the Energy Return on (energy) Investment (EROI) of Corn Ethanol." *Environment, Development and Sustainability* 13, no. 1 (July 11, 2010): 179–202. http://www.springerlink.com/index/10.1007/s10668-010-9255-7. This study is actually less favorable and finds a neutral 1:1 EROI. Two USDA-funded studies have found values of 1.24:1 in 1995 and 1.34:1 in 2002: 3. Shapouri et al. "Estimating the Net Energy Balance of Corn Ethanol." *Agricultural Economic Report* 721 (July 1995). http://content.imamu.edu.sa/Scholars/it/net/usda_shapouri.pdf;

and 4. Shapouri et al . *The Energy Balance of Corn Ethanol: An Update*. US Department of Agriculture, July 2002.

[49] Shapouri and Salassi. *The Economic Feasibility of Ethanol Production from Sugar in the United States*. US Department of Agriculture, July 2006. http://www.lsuagcenter.com/NR/rdonlyres/0EF2C03C-1C69-455E-AB51-C16D165C2F41/28608/EthanolSugarFeasibilityReport3Julyreleasedcopy.pdf

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[51] Pimentel et al., "Ethanol Production: Energy and Economic Issues Related to U.S. and Brazilian Sugarcane." *Natural Resources Research* 16, no. 3 (August 21, 2007): 235–242. http://www.springerlink.com/index/10.1007/s11053-007-9049-2.

[52] "Emission Factor Documentation for AP-42 Section 1.8 Bagasse Combustion in Sugar Mills." Environmental Protection Agency, April 1993. http://www.epa.gov/ttn/chief/ap42/ch01/bgdocs/b01s08.pdf.

[53] "Revised Totals for South-Central Brazil Sugarcane Harvest Show Even Smaller Cane Crush for 2011/2012 Season." *SugarCane.org*, November 1, 2011. http://sugarcane.org/media-center/sugarcane-statistics/2011/revised-totals-for-south-central-brazil-sugarcane-harvest2028show-even-smaller-cane-crush-for-2011-2012-season-1.

[54] See 1. Foreign Agricultural Service. *Brazil Biofuels Annual Report 2012*. US Department of Agriculture, August 21, 2012. http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-21-2012.pdf; and 2. "Short-Term Energy Outlook." *Energy Information Administration*, December 11, 2012. http://www.eia.gov/forecasts/steo/report/renew_co2.cfm.

[55] Patzek. "A Probabilistic Analysis of the Switchgrass Ethanol Cycle."

[56] Questionably optimistic EROI prediction found in 1. M. R. Schmer et al., "Net energy of cellulosic ethanol from switchgrass," *Proceedings of the National Academy of Sciences* 105, no. 2 (January 15, 2008): 464 -469. For a more conservative analysis, and one which has proven to be more predictive, see 2. Pimentel and Patzek, "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower," *Natural Resources Research* 14, no. 1 (March 2005): 65-76.

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[61] "The October Surprise: BP Cancels Plans for US Cellulosic Ethanol Plant." *Renewable Energy World*, October 26, 2012. http://www.renewableenergyworld.com/rea/news/article/2012/10/the-october-surprise-bp-cancels-plans-for-us-cellulosic-ethanol-plant.

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http://www.renewableenergyworld.com/rea/news/article/2011/01/shell-exits-algae-as-it-commences-year-of-choices.

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[66] Matthew Wald, "Companies Face Fines for Not Using Unavailable Biofuel." *New York Times*, January 9, 2012. http://www.nytimes.com/2012/01/10/business/energy-environment/companies-face-fines-for-not-using-unavailable-biofuel.html.

[67] See 1. Jim Lane. "Coskata Switches Focus from Biomass to Natural Gas; to Raise $100M in Natgas-oriented Private Placement." *Biofuels Digest*, July 20, 2012. http://www.biofuelsdigest.com/bdigest/2012/07/20/coskata-switches-from-biomass-to-natural-gas-to-raise-100m-in-natgas-oriented-private-placement/; and 2. Kevin Bullis, "Biofuels Companies Drop Biomass and Turn to Natural Gas."

[68] "Carbohydrates are not a substitute for oil. I was wrong in that, and I admit it. [They] will never replace oil because the economics don't work. You can't take carbohydrates and convert them into hydrocarbons economically. . . . It's a death blow that that maximum yield is about 30 percent." Alan Shaw (former CEO of Codexis) as quoted in Kevin Bullis, "Biofuels Companies Drop Biomass and Turn to Natural Gas."

[69] For soybean productivity see 1. Robert Wisner. "Soybean Oil and Biodiesel Usage Projections & Balance Sheet". Iowa State University, July 23, 2012. http://www.extension.iastate.edu/agdm/crops/outlook/biodieselbalancesheet.pdf. Peak US soy biodiesel productivity over last five seasons of 502 lb/acre converted from pounds to gallons using density of 7.41 lb/gal. Corn yield of 500 gal/acre-yr is slightly more optimistic than actual corn ethanol yield of 478 gal/acre reported in 2. Mueller, Steffan. "News from Corn Ethanol: Energy Use, Co-Products, and Land Use" presented at the Near-term Opportunities for Bio-refineries Symposium, Champaign IL, October 11, 2010. http://bioenergy.illinois.edu/news/biorefinery/pp_mueller.pdf.

[70] Hill et al.

[71] Keane, Eamon. "Algae Biofuels - Not Sustainable." Seeking Alpha. Accessed January 13, 2012. http://seekingalpha.com/article/185070-algae-biofuels-not-sustainable.

[72] See 1. Pfromm et al. "Sustainability of Algae Derived Biodiesel: A Mass Balance Approach." *Bioresource Technology* 102, no. 2 (January 2011): 1185–1193. http://www.sciencedirect.com/science/article/pii/S0960852410015634. The only exception to the limitations above this author could find in published research is that scientists from Brookhaven National Lab, report that if you feed algae acetate, they will continue to reproduce while still producing oil. The problem is that acetate is a direct synthesis product of petroleum, so the research merely proves that feeding algae a pure oil-based diet causes them to produce more oil. This is a signature example of using petroleum energy to make biofuel with diminished returns. See 2. Fan et al. "Oil Accumulation Is Controlled by Carbon Precursor Supply for Fatty Acid Synthesis in Chlamydomonas Reinhardtii." *Plant & Cell Physiology* (May 28, 2012). doi:10.1093/pcp/pcs082.

[73] National Research Council - Committee on the Sustainable Development of Algal Biofuels. *Sustainable Development of Algal Biofuels in the United States*. Washington, D.C.: The National Academies Press, October 2012. http://www.nap.edu/catalog.php?record_id=13437.

[74] Photosynthetic stoichiometry for typical microalgae: 99.5 CO_2 + 75.5 H_2O + 7.5 $CO(NH_2)_2$ + ½ P_2O_5 (+ sunlight) -> [C_{107} H_{181} O_{45} N_{15} P] + 119.75 O_2 [carbon dioxide + water + urea + phosphate (+ sunlight) -> microalgae + oxygen]. In this example, all of the nitrogen in the microalgae is from urea, and one-sixth of the hydrogen (30 of 181 atoms) is from energetic urea, not inert water. Most algae is grown heterotrophically with some nitrogen, hydrogen, or carbon energy being provided in amoniacal or saccharine form. Autotrophic algae growth requires only CO_2, water, phosphate, micronutrients, and sunlight, but delivers diminished yields. See Frank et al., *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model*. Argonne National Laboratory: Energy Systems Division, April 2008. http://greet.es.anl.gov/publication-algal_lipid_fuels.

[75] "Solazyme Inc. Form 10-Q". Securities and Exchange Commission, November 8, 2011. http://www.faqs.org/sec-filings/111108/SOLAZYME-INC_10-Q/.

[76] Rapier, Robert. "Visit and Conversation With Executives at Solazyme." *Consumer Energy Report*, October 23, 2011. http://www.consumerenergyreport.com/2011/10/23/visit-and-conversation-with-executives-at-solazyme/.

[77] An EROI of 1.06:1 (317 GJ output v. ~300 GJ input) was reported if sun-dried product algal biomass was burned whole in a furnace extracting a thermodynamically perfect 100% of the HHV with no attempt to convert to a liquid fuel. See 1. Clarens, Andres F., Eleazer P. Resurreccion, Mark A. White, and Lisa M. Colosi. "Environmental Life Cycle Comparison of Algae to Other Bioenergy

Feedstocks." *Environmental Science & Technology* 44, no. 5 (March 2010): 1813–1819. http://pubs.acs.org/doi/abs/10.1021/es902838n. A study that considered the costly biomass-to-liquid fuel conversion step found that the input energy required just to circulate the water in the cultivation ponds/tanks exceeded the output biodiesel fuel energy by a factor of seven. See 2. Murphy et al. "Energy-Water Nexus for Mass Cultivation of Algae." *Environmental Science & Technology* 45, no. 13 (July 2011): 5861–5868.

[78] Frank et al. Total energy to produce one functional unit of algae biodiesel of 2,589,441 BTU v. 219,183 BTU to make on functional unit of conventional low-sulfur diesel = 11.8:1 ratio. Well-to-pump fossil fuel energy costs of 548,329 BTU v. 215,388 BTU yield a ratio of 2.6:1.

[79] Fast pyrolysis bio-oil has a specific gravity of 1.24 compared to .079 for ethanol per Ringer, and Scahill. *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis*. National Renewable Energy Laboratory, November 2006.

[80] Raw bio-oils are not suitable feedstock for current refineries because they are too acidic and require 317 stainless steel cladding. Additional pre-processing must be done before they can be upgraded. See Huber, George W., ed. *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels: Next Generation Hydrocarbon Biorefineries*. Washington, D.C.: National Science Foundation: Chemical, Bioengineering, Environmental, and Transport Systems Division, 2008. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.161.2029&rep=rep1&type=pdf.

[81] The alkalinity of bio-char can only offset about 1/5 of the soil acidity resulting from full ammonia fertilization. Laird et al. "Review of the Pyrolysis Platform for Coproducing Bio-oil and Biochar." *Biofuels, Bioproducts and Biorefining* 3, no. 5 (2009): 547–562. http://onlinelibrary.wiley.com/doi/10.1002/bbb.169/abstract.

[82] The gravimetric energy density of charcoal (C_7H_4O) is 30 MJ/kg. It is a chief ingredient of gunpowder.

[83] 565 million acres of trees in the lower 48 states and 185 million acres in Alaska equals 750 million total acres per U.S. Geological Survey. "Biology: Forest Cover Types." Accessed December 18, 2012. http://www.nationalatlas.gov/mapmaker?AppCmd=CUSTOM&LayerList=opchar%3B2&visCats=CAT-agri,CAT-opchar.

[84] "The Indirect Land Use Change Impact of the Use of Biofuels in the EU." *Institute for European Environmental Policy*, March 2011.

http://www.ieep.eu/assets/786/Analysis_of_ILUC_Based_on_the_National_Renewable_Energy_Action_Plans.pdf.

[85] See 1. Hall et al. "What Is the Minimum EROI That a Sustainable Society Must Have?"; and 2. Murphy et al. "New Perspectives on the Energy Return on (energy) Investment (EROI) of Corn Ethanol." *Environment, Development and Sustainability* 13, no. 1 (July 11, 2010): 179–202. doi:10.1007/s10668-010-9255-7.

[86] See 1. Hall et al., "What is the Minimum EROI that a Sustainable Society Must Have?"; and 2. Murphy et al., "Year in review—EROI or energy return on (energy) invested," *Annals of the New York Academy of Sciences* 1185, no. 1 (January 1, 2010): 102-118.

[87] For a long-term depiction of petroleum EROI, see Guilford et al. "A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production." *Sustainability* 3, no. 10 (October 14, 2011): 1866–1887. http://www.mdpi.com//2071-1050/3/10/1866/. Current US petroleum fuel EROIs are estimated between 11:1 and 18:1, and coal EROIs are estimated as high as 80:1, so using 8:1 in this analysis as representative of all fossil fuel inputs to corn ethanol processing is very prejudicial against fossil fuel, and the corn ethanol numbers are likely more negative. For recent oil and coal EROI discussion, see Hall et al. "What Is the Minimum EROI That a Sustainable Society Must Have?"

[88] The term "barrel of energy" is used here to represent a generic unit of energy for relative comparison purposes. The value is more specifically defined as the energy in a barrel of crude oil and has a value of 6.1306 GJ = 1.7029 MWh = 5.8106 MBTU. A barrel of crude oil has virtually the same energy content as a barrel of diesel fuel.

[89] The fraction of crude oil that yields fuels vice feedstocks is based on 1. "What a Barrel of Crude Oil Makes." *Texas Oil & Gas Association*, accessed July 8, 2012. http://www.txoga.org/articles/308/1/WHAT-A-BARREL-OF-CRUDE-OIL-MAKES. On average, 42 gallons of crude oil become 19.5 of gasoline, 9.2 of diesel and heating oil, 4.1 of jet fuel, 2.3 of heavy fuel oil for ships and powerplants, 1.9 in liquefied butane and propane, 1.9 in still gas used within the refinery, 1.8 in coke, 1.3 in asphalt and road oil, 1.2 in petrochemical feedstocks, 0.5 in lubricants, 0.2 in kerosene, and 0.3 in other. 5.1 gallons are non-fuel items with industrial utility. Computing CO_2 emissions from the fossil fuel creation assuming input energy is diesel fuel: 1 bbl x 42 gal/bbl of diesel @ 23.66 lb CO_2/gal for diesel combustion = 944 lb. CO_2 from product fuel combustion: 9 bbl of crude x 42 gal/bbl x 22.99 lb CO_2/gal for crude combustion = 8,690 lb. Total CO_2: 944 lb + 8,690 lb = 9,634 lb (counting all fuel and non-fuel carbon on the page = worst case). Input H_2O: 9 bbl x 42 gal/bbl x 6.6 gal/gal = 2,495 gal. Water footprint of petroleum covers all extraction and refining processes including water injection into older oil fields for secondary recovery. Maximum value of 6.6 gallons water per gallon of gasoline is

used to make the calculation as conservative as possible and is based on 2. Wu et al. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline - 2011 Update*. Argonne National Laboratory: Energy Systems Division, July 2011.

[90] Figure 5 depicts same net energy output as Figure 4 (i.e., 8 bbl diesel equivalent). Each barrel of diesel equivalent energy input yields energy parity in 1.63 barrels of ethanol plus a 0.25 barrel diesel equivalent net energy profit in co-product of DDGS. Ethanol has 0.615 times the volumetric energy density of diesel, therefore it takes 52 bbl of ethanol to equal the energy in 32 bbl of diesel. Values of 478 gal/acre ethanol yield and 5 lb/gal of ethanol in DDGS yield are per 2008 survey of 90 dry-mill ethanol refineries as reported in 1. Mueller, Steffan. "News from Corn Ethanol: Energy Use, Co-Products, and Land Use" presented at the *Near-term Opportunities for Bio-refineries Symposium*, Champaign IL, October 11, 2010. http://bioenergy.illinois.edu/news/biorefinery/pp_mueller.pdf. Acreage of cornfield required: 52 bbl x 42 gal/bbl = 2,184 gal ÷ 478 gal/acre = 4.57 acre. DDGS co-product: 5 lb/gal x 2,184 gal = 10,920 lb. CO_2 from fuel creation: 32 bbl x 42 gal/bbl x 23.66 lb CO_2/gal diesel = 31,799 lb. No CO_2 is charged for ethanol or DDGS consumption. Conservative calculation of CO_2-equivalent (CO_2e) N_2O emissions from corn fertilization: 2% of 150 lb/acre NH_3 x 4.6 acre = 13.8 lb NH_3 x 82.35% N mass fraction of NH_3 = 11.36 lb of N ÷ 63.64% N mass fraction of N_2O = 17.86 lb of N_2O x 298 multiplier for CO_2 warming potential equivalence = 5,321 lb CO2e. Total CO_2e emissions: 31,799 lb CO_2 + 5,321 lb CO_2e = 37,120 lb CO_2e. H_2O for ethanol: 52 bbl x 42 gal/bbl x 1,220 gal/gal = 2.66 million gal. (U.S. average corn ethanol water footprint per 2. Gerbens-Leenes and Hoekstra. The Water Footprint of Sweeteners and Bio-ethanol from Sugar Cane, Sugar Beet and Maize. Value of Water Research Report Series. UNESCO Institute for Water Education, November 2009. http://www.waterfootprint.org/Reports/Report38-WaterFootprint-sweeteners-ethanol.pdf. H_2O for diesel: 32 bbl x 42 gal/bbl x 6.6 gal/gal = 8,870 gal. Total H_20: 2.66 million gal + .009 million gal = 2.67 million gal.

[91] Hall et al. "Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels."

[92] For the firmly established correlation between EROI and price, see 1. King and Hall. "Relating Financial and Energy Return on Investment." *Sustainability* 3, no. 10 (October 11, 2011): 1810–1832. doi:10.3390/su3101810; and 2. Murphy, David J., Charles A. S. Hall, and Bobby Powers. "New Perspectives on the Energy Return on (energy) Investment (EROI) of Corn Ethanol." *Environment, Development and Sustainability* 13, no. 1 (July 11, 2010): 179–202. doi:10.1007/s10668-010-9255-7.

[93] The pure corn ethanol EROI can be derived by dividing the petroleum-corn ethanol hybrid EROI of 1.25:1 by the pure petroleum EROI of 8:1 discussed earlier to yield 0.156:1 = 1:6.4.

[94] An alternative source of hydrogen is electrolysis from water. This could only be done with massive new sources of electrical power. Using hydroelectric power to electrolyze hydrogen was promoted 100 years ago by Nikola Tesla. If such excess power capacity was available today, we would use the resulting hydrogen directly as fuel and dispense with biofuels, not redirect hydrogen into the less efficient process of making fertilizer for growing biomass for conversion into fuel. This is exactly the same argument for not wasting fossil fuels for this purpose.

[95] Galouchko, Ksenia. "Ethanol Follows Gasoline Higher After Iran Blocks Base Access." *Bloomberg*, February 22, 2012. http://www.bloomberg.com/news/2012-02-22/ethanol-follows-gasoline-higher-after-iran-blocks-base-access.html.

[96] Wilson, Conrad. "High Corn Prices Force Ethanol Plant Shutdowns." *MPR News*, August 28, 2012. http://minnesota.publicradio.org/display/web/2012/08/28/business/agriculture-ethanol-drought/.

[97] Similar graph using US government data available at "Alternative Fuels Data Center." Department of Energy, October 2012. http://www.afdc.energy.gov/data/tab/all/data_set/10323.

[98] For a plot of US ethanol production that follows a perfect Hubbert curve, see "Alternative Fuels Data Center." Department of Energy, October 2012. http://www.afdc.energy.gov/data/tab/all/data_set/10323. Demand-side issues that were ignored by Hubbert are as important in shaping production peaks as supply-side issues such as scarcity. This author has found that a logistic curve (classic sigmoid) with an inflection point in 1945 fits US oil production data from its inception in1859 through the global price collapse of 1986 better than a Hubbert curve (symmetrical sigmoid). The underlying competitive dynamics which drive logistic curves (market share, market penetration, carrying capacity, etc.) also better explain why global crude oil production continues to grow slowly rather than falling off symmetrically as would be the case if increasing scarcity of supply was the dominant factor.

[99] US federal government required production of 13.2 billion gallons of corn ethanol in 2012 for gasoline blending per Environmental Protection Agency, "2012 Renewable Fuel Standards; Final Rule," Vol. 77. 5th ed. *Federal Register*, 2012. http://www.gpo.gov/fdsys/pkg/FR-2012-01-09/pdf/2011-33451.pdf. While the mandate for 2013 increases to 13.8 billion gallons, the additional margin and more

is likely to be met with accumulated Renewable Energy Credits (REC). US corn ethanol biorefineries have been losing money on each gallon of ethanol since July 2012 because of falling oil prices due to increased global production and rising corn prices due to the drought.

[100] See 1. King, C. W. "Energy Intensity Ratios as Net Energy Measures of United States Energy Production and Expenditures." *Environmental Research Letters* 5, no. 4 (October 1, 2010): 044006; and 2. King and Hall. "Relating Financial and Energy Return on Investment." *Sustainability* 3, no. 10 (October 11, 2011): 1810–1832.

[101] Leonnig et al. "Obama Green-tech Program That Backed Solyndra Struggles to Create Jobs." *The Washington Post*, September 15, 2011, sec. Business. http://www.washingtonpost.com/politics/obama-green-tech-program-that-backed-solyndra-struggles-to-create-jobs/2011/09/07/gIQA9Zs3SK_story.html.

[102] "Operational Energy Strategy". *Department of Defense*, May 2011. http://energy.defense.gov/Operational_Energy_Strategy.pdf.

[103] David Miller. "Biofuels Conference: Secretary of the Navy Says Military Can Lead the Way in Alternative Energy." *The Dispatch*. Starkville MS, October 7, 2011. http://www.cdispatch.com/news/article.asp?aid=13418.

[104] $25.73 per gallon for Amyris direct sugar-to-hydrocarbon diesel (DSH) biofuel x 42 gallon/barrel = $1,080.66 per barrel. Highest price paid by Navy was $4,454.55 per gallon = $187,091.10 per barrel. See Table 1 for details.

[105] Contract quantity and price data pulled from official government websites in 2012 and tabulated by contract number in Table 1. Sources include 1. General Services Administration Federal Procurement Data System - Next Generation search page, https://www.fpds.gov/fpdsng_cms/; 2. FedBizOpps.gov website search page. https://www.fbo.gov/; 3. "Bulk Petroleum Contract Awards." *Defense Logistics Agency – Energy*. http://www.energy.dla.mil/bulk_petroleum/Pages/Contract_Awards.aspx; and 4. *DLA Energy Fact Book FY2011.* Defense Logistics Agency - Energy, 2011. http://www.energy.dla.mil/energy_enterprise/Documents/Fact%20Book%20FY2011%20Rev.pdf.

[106] Nerurkar, Neelesh. *US Oil Imports: Context and Considerations*. Congressional Research Service, April 1, 2011. https://opencrs.com/document/R41765/.

[107] See 1. *Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2010*. Energy Information Agency, July 2011. http://www.eia.gov/analysis/requests/subsidy/; and 2. Annual Energy Review 2011. http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf. Subsidy amounts

for energy sources in Table ES2 from the first reference are divided by 2010 data for US energy production for the respective sources from the second reference.

[108] US Department of Energy, "DOE Recovery Act Funding," *Energy.gov*, December 2011, http://energy.gov/sites/prod/files/recoveryactfunding.xls.

[109] Mabus, Chu, and Vilsack. "Memorandum of Understanding Between the Department of the Navy and the Department of Energy and the Department of Agriculture," June 28, 2011. http://www.rurdev.usda.gov/SupportDocuments/DPASignedMOUEnergyNavyUSDA.pdf.

[110] "AAA's. Daily Fuel Gauge Report." *American Automobile Association*, July 19, 2012. http://fuelgaugereport.opisnet.com/index.asp.

[111] A gallon of ethanol contains only 2/3 the energy of a gallon of gasoline; if priced at energy parity, it would be 2/3 the price. 2010 average retail gasoline price (minus 18.4 cent/gal federal excise tax) = $2.58/gal x 2/3 = $1.72/gal (what ethanol should have cost). 2010 average retail E85 price = $2.40/gal (what retail ethanol did cost to a close approximation). How much consumers overpaid at pump = $2.40/gal – $1.72/gal = $0.68/gal x 12 billion gal blended in 2010 = $8.1 billion. For 2010 fuel prices and $6.1 billion in tax credits see Table 17-1 and footnotes in Office of Management and Budget. *Budget of the U.S. Government: Analytical Perspective Fiscal Year 2012.* Executive Office of the President, 2011; and Table A12 of *Annual Energy Outlook 2012*. Energy Information Agency, June 2012. http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf.

[112] Hargreaves, Steve. "Gasoline: The New Big U.S. Export." *CNN Money*, December 5, 2011. http://money.cnn.com/2011/12/05/news/economy/gasoline_export/index.htm.

[113] See note 105 above.

[114] 2009 tax data is presented as it is the most recent made available by EIA. 2009 was a particularly bad year for IRS revenue from oil company taxes because of the economic crash, and 2010 data is likely much higher. Oil companies paid $13.7 billion in corporate taxes and consumers paid $42.4 billion in excise taxes for a total of $56.1 billion in federal government revenues per "EIA Financial Reporting System Survey - Form EIA-28 Schedule 5112 - Analysis of Income Taxes." *Energy Information Agency*, 2009. ftp://ftp.eia.doe.gov/pub/energy.overview/frs/s5112.xls. Dividing $56.1 billion by the 6.23 billion barrels of oil and gas domestically produced in 2010 yields $9.01

per barrel. Federal excise taxes paid by consumers at the pump are 18.4 cents per gallon for gasoline and 24.4 cents per gallon for diesel.

[115] "Market Cap Stock Rankings for Major Integrated Oil & Gas Industry." *YCharts*, January 7, 2013. http://ycharts.com/rankings/industries/Major%20Integrated%20Oil%20&%20Gas/market_cap.

[116] "GDP." World Bank, 2011. http://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

[117] Annual Energy Review 2011. Energy Information Agency, September 27, 2012. http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.

[118] Slade et al.

[119] See note 21 for solar power density derivation. Wind power density of 1.13 W/m^2 based on recent NREL data reporting 2.9 W/m^2 peak and 39% capacity factor as averaged across 2000-2009 US installations with nameplate capacity > 20MW). See 1. Denholm et al. *Land-Use Requirements of Modern Wind Power Plants in the U.S.* National Renewable Energy Laboratory, August 2009. www.nrel.gov/docs/fy09osti/45834.pdf. Corn ethanol power density of 0.315 W/m^2 based on 500 gal/acre-yr @ 76,321 BTU/gal LHV. Soy biodiesel power density of 0.069 W/m^2 based on 70 gal/acre-yr @ 119,545 BTU/gal LHV. Average US crude oil well in 2011 produced 10.6 barrels crude oil per day @ 129,667 BTU/gal on a two-acre parcel of land, which equates to ~90 W/m^2. See 2. *Annual Energy Review 2011*. http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.

[120] Patzek. "A Probabilistic Analysis of the Switchgrass Ethanol Cycle."

[121] Jeavons, John. *How to Grow More Vegetables: And Fruits, Nuts, Berries, Grains and Other Crops Than You Ever Thought Possible on Less Land Than You Can Imagine*. 6th ed. Ten Speed Press, 2004.

[122] DoE NREL research has calculated the best case for algae yields from pure solar energy without fossil fuel or sugar energy augmentation to be 6,500 gal/acre-yr biodiesel = 17.8 gal/acre-day = 6.42 W/m^2 LHV. Sapphire Energy projects it will achieve 14 gal/acre-day of algae biodiesel from 300 acres by 2014. See 1. "In Race to Algae Fuel, Sapphire Scores Point for Open Ponds." Sapphire Energy, September 6, 2012. http://www.sapphireenergy.com/news-article/1135734-in-race-to-algae-fuel-sapphire. Algenol, using cyanobacteria animal algae instead of microphyte plant algae, and producing ethanol instead of lipids, recently announced it achieved 21.9 gal/acre-day of ethanol. This is equivalent to 5.6 W/m^2 and still

below today's PV solar. See 2. Woods, Paul. "About Algenol." Algenol Biofuels, September 27, 2012. http://www.algenolbiofuels.com/.

[123] See 1. Perlack et al. US Department of Agriculture and Department of Energy. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-ton Annual Supply*. Oak Ridge, TN: Oak Ridge National Laboratory, 2005. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA436753; and 2. R.D. Perlack and B.J. Stokes (leads). US Department of Energy. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Oak Ridge, TN: Oak Ridge National Laboratory, 2011. http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf.

[124] Jennifer Franco et al. "The Global Land Grab: A Primer". Transnational Institute, October 11, 2012. http://www.tni.org/primer/global-land-grab.

[125] "Home." *Blue Sugars Corporation*. Accessed October 8, 2012. http://bluesugars.com/index.htm.

[126] Haddok, Eitan. "Biofuels Land Grab: Guatemala's Farmers Lose Plots and Prosperity to 'Energy Independence'." *Scientific American*, January 13, 2012. http://www.scientificamerican.com/article.cfm?id=biofuels-land-grab-guatemala.

[127] Deininger, Klaus W, Derek Byerlee, and World Bank. *Rising Global Interest in Farmland: Can It Yield Sustainable and Equitable benefits?* Washington, D.C.: World Bank, 2011. http://siteresources.worldbank.org/INTARD/Resources/ESW_Sept7_final_final.pdf.

[128] Gallagher, Ed. *The Gallagher Review of the Indirect Effects of Biofuels Production*. East Sussex, UK: Renewable Fuels Agency, July 2008. http://www.unido.org/fileadmin/user_media/UNIDO_Header_Site/Subsites/Green_Industry_Asia_Conference__Maanila_/GC13/Gallagher_Report.pdf.

[129] As biofuel competition with food and the magnitude of GHG released from land use change to cultivation have become undeniably apparent, advocates of biofuels have shifted their focus away from use of every acre of arable land toward use of "degraded" or "marginal" land. However, as shown, biofuels crops are as energy-hungry as food crops, and if grown on marginal land, their energy yields will be equally marginal. The very concept of degraded land is also questionable. To the extent that the ingredients necessary for life exist on a parcel of land, life is already there fixing carbon in the soil and in its biomass as fast as it can. Even the most barren plot of land is covered with the dormant seeds and spores of life just

waiting for the water or other missing ingredient to appear or the toxin levels to subside. Unless reclaiming the Sahara and Gobi and Antarctic deserts or urban parking lots, new crops are always going to displace some other species that was there first already taking full advantage of the available sun and soil energy to sequester carbon.

[130] 1. IPCC, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, prepared by the National Greenhouse Gas Inventories Programme [Institute for Global Environmental Strategies (IGES), Tokyo, Japan, 2007. 2. Searchinger et al. "Fixing a Critical Climate Accounting Error." *Science* 326, no. 5952 (October 23, 2009): 527–528. http://www.sciencemag.org/content/326/5952/527.

[131] For seven examples of recent studies finding biofuels increase GHG and environmentally damaging emissions, see 1. Jaeger and Egelkraut. "Biofuel Economics in a Setting of Multiple Objectives and Unintended Consequences." *Renewable and Sustainable Energy Reviews* 15, no. 9 (December 2011): 4320–4333. http://www.sciencedaily.com/releases/2011/11/111129123255.htm; 2. Yang et al. "Replacing Gasoline with Corn Ethanol Results in Significant Environmental Problem-Shifting." *Environmental Science & Technology* (March 14, 2012): 120314152159007. http://pubs.acs.org/doi/abs/10.1021/es203641p; 3. Smith and Searchinger. "Crop-based Biofuels and Associated Environmental Concerns." *GCB Bioenergy* (June 2012). http://www.sciencedaily.com/releases/2012/06/120608100548.htm; 4. Thomas Walker et al. *Biomass Sustainability and Carbon Policy Study*. Manomet Center for Conservation Sciences, June 2010. http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf; 5. Scharlemann et al., "How Green Are Biofuels?," *Science* 319, no. 5859 (January 4, 2008): 43-44; 6. "Alternative Fuels and Advanced Vehicles Data Center: E10 Emissions." *Department of Energy*, January 28, 2011. http://www.afdc.energy.gov/afdc/vehicles/emissions_e10.html; and 7. Hill et al.

[132] Hitz, S. "The Role of Oxygenated Fuel in California Air Quality." University of California, 1999. https://bren.ucsb.edu/research/1999Group_Projects/airquality/airquality_final.pdf.

[133] See 1. Franklin et al. "Clearing the Air: Using Scientific Information to Regulate Reformulated Fuels." *Environmental Science & Technology* 34, no. 18 (September 1, 2000): 3857–3863. http://dx.doi.org/10.1021/es0010103; 2. Rask, Kevin. "Clean Air Policy and Oxygenated Fuels: Do We Get What We Pay For?" *Energy Economics* 26, no. 1 (January 2004): 161–177. doi:10.1016/S0140-9883(03)00040-9; and 3. *AQIRP Final Report*. Auto/Oil Air Quality Improvement Research Program, January 1997. http://www.crcao.com/reports/auto-oil/Default.htm.

[134] MTBE = Methyl Tertiary Butyl Ether, a fuel oxygenate hastily mandated by the EPA to achieve 1990 Clean Air Act standards, but which had the unfortunate side-effect of increasing groundwater fuel contamination. EPA is responsible for air, soil, and groundwater quality, but still has not connected the dots for ethanol across these domains.

[135] Blue Ribbon Panel on Oxygenates. *Achieving Clean Air and Clean Water*. Environmental Protection Agency, September 15, 1999. http://www.epa.gov/oust/mtbe/brp_usts.htm.

[136] American Institute of Physics. "Mixing Processes Could Increase the Impact of Biofuel Spills on Aquatic Environments." *Phys.Org*, November 16, 2012. http://phys.org/news/2012-11-impact-biofuel-aquatic-environments.html.

[137] Energy content of the ethanol-blended gasoline is reduced 3.3% for E10 and 28% for E85, and this roughly corresponds to reduced MPG.

[138] 42 USC § 7545(h)(4) – Regulation of Fuels. "Ethanol waiver: For fuel blends containing gasoline and 10 percent denatured anhydrous ethanol, the Reid vapor pressure limitation under this subsection shall be one pound per square inch (psi) greater than the applicable Reid vapor pressure limitations."

[139] Blue Ribbon Panel on Oxygenates.

[140] Lewis, Jonathan. *Leaping Before They Looked: Lessons from Europe's Experience with the 2003 Biofuels Directive*. Boston: Clean Air Task Force, October 2007.

[141] In 2011, OECD nations reduced CO2 emissions by 0.6% while non-OECD nations increased CO2 emissions by 6.1%, for a net global increase of 3.2% to a record high of 31.6 billion metric tons ~ 35 billion short tons. See "Global Carbon-dioxide Emissions Increase by 1.0 Gt in 2011 to Record High." International Energy Agency, May 24, 2012. http://www.iea.org/newsroomandevents/news/2012/may/name,27216,en.html.

[142] Ibid.

[143] Annual Energy Review 2011.

[144] Davidson et al. *Excess Nitrogen in the U.S. Environment: Trends, Risks, and Solutions*. Ecological Society of America, Winter 2012. http://www.esa.org/science_resources/issues/FileEnglish/issuesinecology15.pdf.

[145] International Panel on Climate Change. *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, 2007. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm.

[146] "Recent Greenhouse Gas Concentrations." Carbon Dioxide Information Analysis Center, February 2012. http://cdiac.ornl.gov/pns/current_ghg.html.

[147] Ravishankara et al. "Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century." *Science* 326, no. 5949 (August 27, 2009): 123–125. http://www.sciencemag.org/cgi/doi/10.1126/science.1176985.

[148] Crutzen et al. "N2O Release from Agro-biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels." *Atmospheric Chemistry and Physics Discussions* 7, no. 4 (2007): 11191–11205.

[149] According to a nine-nation jointly funded study, if all European governments follow through with their current renewable fuel plans, it will require the conversion to biofuels cultivation of a land area between the size of Belgium and the size of Ireland, and will generate between 81% and 167% more GHG emissions than using straight fossil fuels. See Bowyer, Catherine. "The Indirect Land Use Change Impact of the Use of Biofuels in the EU." *Institute for European Environmental Policy*, March 2011. http://www.ieep.eu/assets/786/Analysis_of_ILUC_Based_on_the_National_Renewable_Energy_Action_Plans.pdf. Also see 1. Righelato et al., "Carbon Mitigation by Biofuels or by Saving and Restoring Forests?," *Science* 317, no. 5840 (2007): 902.

[150] Energy Independence and Security Act of 2007– Section 526. "No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources." "No later than Oct. 1, 2015, and for each year thereafter, each Federal agency shall achieve ≥ 20 percent reduction in annual petroleum consumption and a 10 percent increase in annual alternative fuel consumption, relative to FY2005 baseline."

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